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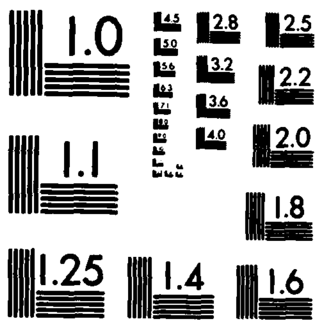
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Proceedings From A Workshop on Economic Analysis of Inland Navigation and Port Projects

15 - 16 March 1984

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Proceedings of a workshop held 15-16 March 1984 at the Pulaski Building, Washington, D.C. 20314-1000. The workshop included Corps technical specialists, several Corps planning managers and outside experts in navigation modelling, economics and simulation to determine where we are and what should be done to increase the quality and effectiveness of the economic analysis of navigation projects.

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PROCEEDINGS FROM A WORKSHOP ON ECONOMIC

ANALYSIS OF INLAND NAVIGATION AND PORT PROJECTS

15-16 March 1984

Sponsored by

U. S. Army Corps of Engineers

Water Resources Support Center

Institute for Water Resources

February 1985

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FOREWARD

This meeting brought most of the Corps technical specialists, several Corps planning managers and some outside experts in navigation modelling, economics and simulation together to determine where we are and what should be done to increase the quality and effectiveness of the economic analysis of navigation projects.

Better communication of the merits and problems of existing capability became an early and urgent issue. Technical jargon interferes with communication even among technical specialists from different disciplines. Therefore, an effort to improve communication is underway.

Corps navigation system models represent an evolutionary process. Since the Corps mission is carried out by decentralized field offices, field personnel have acted to change and improve models developed by centralized research and development programs. They have also created new and fruitful approaches. We believe the mission of the Institute for Water Resources (IWR) Navigation Division is (1) to encourage and broaden this evolutionary process, (2) to support promising new ideas generated by field personnel and (3) to promote interchange of primary approaches.

The Corps research program in economic analysis of navigation projects is proceeding to develop an improved empirical basis and more precise analytical approach to estimating the benefits due to increasing capacity in the navigation system. This meeting reinforced the importance of this effort.

James R. Hanchey

JAMES R. HANCHEY
Director
Institute for Water Resources

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Part I

Summary of Meeting

EXECUTIVE SUMMARY

Background

The Institute for Water Resources sponsored a "Workshop on Economic Analysis of Inland Navigation and Port Projects", in Washington, D.C. on March 15 and 16, 1984. The purpose of the workshop was to review and familiarize Corps of Engineers navigation planners with different navigation models for systems analysis of waterway improvements. The primary focus of the workshop was on systems analysis of inland waterway lock congestion, however, the issues addressed were also applicable to deep draft port studies.

The workshop consisted of four papers on navigation modelling systems analysis. Two different systems analysis models were presented: (1) Marginal Economic Analysis Model (MEA) and Tow Cost Model (TCM); and (2) General Equilibrium Model (GEM). The primary distinctions between the two different systems models are: (1) orientation to supply (MEA/TCM) or demand (GEM) characteristics of the waterways; and (2) methodology utilized to reach a partial or general equilibrium solution to lock congestion. The different approaches have substantial implications for analysis of waterway structural and non-structural improvements.

Three outside experts in navigation modelling, economics and simulation reviewed the papers on Corps navigation modelling. The panel of experts was

in general agreement with the issues raised by the models. The experts expressed that better explanation of the models was needed, particularly the GEM, in addition to model performance and inputs.

Conclusions.

Existing system models are designed to facilitate economic analysis of the benefits which would accrue if capacity is increased at one or more locks (or other constraints permit) in the navigation system. Two basic approaches have evolved in the Corps, (1) a supply oriented emphasis (much detail on lock, channel geometry and tow operations) used by the Ohio River Division and South Atlantic Division in recent reports and (2) a demand oriented emphasis (reduced detail on supply side factors) used by Lower Mississippi Valley Division and North Central Division in recent reports. Each approach ought to give similar results if common inputs are utilized. Each approach gives added information in some areas. Each approach has some computer system advantages and disadvantages. Finally, the best possible strategy for the Corps is (1) to improve the written description of each approach to remove computer, mathematical and economic jargon, and to increase the information about required input data and assumptions, and (2) to promote exchange of analysis models between Districts, Divisions and other Corps offices.

Recommendations.

1. Develop user manuals and executive summaries of the General Equilibrium Model, the Tow Cost - Marginal Economic Analysis Model and the

Waterway Analysis Model. Each manual and summary would contain a simple exposition of what each model does and how it operates. Additional information to guide computer systems and navigation analysts would be included, so they can operate the models.

2. Begin the interchange of models between Corps offices. The first step would be a hands on test of the GEM and a comparison with the Tow Cost - Marginal Economic Analysis model at the Huntington District Navigation Support Center.

3. Continue research on the economic analysis of congestion and the benefits from adding capacity to the navigation system.

OVERVIEW

Navigation modelling by the Army Corps of Engineers (Corps) has made substaintial progress in both sophistication and the types of issues addressed. The increased sophistication has resulted from a variety of conceptual issues, theoretical developments, modelling refinements, and increased efficiency of computer techniques that have been adapted to navigation modelling. Before 1970 evaluation of navigation improvements was generally conducted using a single lock model that ignored any systemic relationships of the lock to other components of the navigation system. Although major conceptual and theoretical problems associated with the single lock model were recognized, computational constraints generally prohibited incorporation of systemic impacts except through the introduction of heuristic devices.

Beginning in 1974 a number of improvements began to be incorporated into navigation models utilized by the Corps. The development of more robust navigation models progressed slowly, largely due to computer constraints and the long lead-times which characterized the specification of systemic impacts in navigation models. However, by 1978 the Corps had constructed a set of sophisticated, interactive computer models suitable for further development through testing, calibrating, and subsequent modifications through application to project evaluation. This development was undertaken by the Ohio River Division (ORD) in the evaluation of Gallipolis Locks and Dam beginning in 1978.

Concurrently with the efforts of ORD, the St. Louis Division (SLD) was involved in a series of navigation studies. Although the

basic issues addressed by both districts were the same, the models subsequently developed by SLD emphasized demand-side characteristics of the waterway system and the resulting implications on systemic impacts and equilibrium. The ORD models, however, placed greater emphasis on supply-side characteristics and the resulting implications on systemic impacts and equilibrium. Both sets of models explicitly incorporated supply and demand characteristics of the navigation system. The emphasis of either supply or demand reflects a judgment of the level of detail necessary to specify determinants of navigation conditions, rather than a judgment that either demand or supply is more important within a system framework. Consequently, each set of models had strengths and weaknesses that could only be assessed in relation to the supply and demand characteristics of a particular waterway.

To provide for a broader understanding of the issues involved in navigation modelling the Institute for Water Resources (IWR) held a "Workshop on Economic Analysis of Inland Navigation and Port Projects" in Washington, D.C. on March 15 and 16, 1984. The purpose of the workshop was to provide a forum for discussing the modelling capabilities of the Corps and to foster continued development of navigation modelling. The purpose of the workship was summarized by Dr. Blakey as not to promote any single model or methodology for use in project evaluation, but to promote the understanding of available models and their application in navigation evaluation.

To accomplish this objective four papers on navigation modelling were presented at the workshop. Discussants were invited to review the

papers and participate in the workshop. This arrangement maximized the breadth and depth of experience and views on navigation modelling and project evaluation. The four papers presented and reviewed by discussants were as follows:

"An Overview of Waterway Systems Analysis Capability and Problems", Dr. Lloyd G. Antle, Chief, Navigation Analysis Division, Institute for Water Resources, Fort Belvoir, Virginia.

"Systems Evaluation", Ron Keeney, Huntington District, Ohio River Division, U. S. Army Corps of Engineers (March 1984).

"A System Equilibrium Model for Economic Policy Analysis of National Inland Waterways Navigation", Donald M. Sweeney, St. Louis District, Lower Mississippi River Division, U. S. Army Corps of Engineers (December 1983).

"A Nonlinear Programming Model to Measure Economic Impacts of Inland Navigation", Donald M. Sweeney and Dr. Michael Healy St. Louis District and Boeing Computer Services (February 1984).

These papers will be referred to as "Overview", "Systems Evaluation", "GEM I" and "GEM II", respectively.

Dr. Blakey opened the workshop with a keynote address which was immediately followed by an independent assessment of the four papers on existing models and issues related to navigation modelling by three discussants: (1) Dr. Michael S. Bronzini, University of Tennessee; (2) Dr. J. Royce Ginn, Cambridge Information International; and (3) Dr. Leonard Shabman, Virginia Polytechnic Institute and State University.

Each discussant spoke on different facets of the four papers he

reviewed. Dr. Ginn concentrated on the GEM I and GEM II papers, reviewing the issues and the potential problems that may be embodied in the modelling portrayed by these papers. Dr. Shabman focused on the Overview paper and the implications of Corps navigation modelling efforts for economic principles and the degree to which the models meet regulatory principles and guidelines. Dr. Bronzini presented an overview of the evolution of navigation systems modelling and discussed some of the important assumptions embodied in the Systems Evaluation paper related to the Tow Cost Model (TCM). He concluded with general comments on the GEM papers, emphasizing the need for a better intuitive exposition of each paper and that the solution methodology for the problem formulated in the papers was also available using the equilibrium trip assignment method.

After comments by discussants the authors of the four papers made formal presentations. Dr. Antle presented an overview of economic analysis related to lock congestion and the need for additional research to better specify lock congestion impacts and responses. Ron Keeney addressed two navigation models used by ORD for the study of Gallipolis Locks and Dam: (1) Tow Cost Model (TCM); and (2) Marginal Economic Analysis Model (MEA). Mr. Keeney emphasized that the modelling efforts embodied in the TCM and MEA were orientated to the supply-side, particularly in specifying the response of tow costs to changes in traffic levels and lock congestion.

Don Sweeney presented a general overview of the modelling issues that led to the development of the General Equilibrium Model (GEM). The

issues he cited were: (1) model statistics; (2) calibration problems; (3) traffic diversion criteria; (4) data requirements; (5) verification of model results; and (6) unwieldness of large scale simulation models. Mr. Sweeney noted that the evolution of GEM began with a single lock model that was extended to include additional system components and the relationships between system components. Due to the complexities involved in solving a large scale equilbrium problem, it was necessary to construct GEM so that it could utilize relatively new and advanced computer techniques and solution algorithms.

Dr. Healy followed with a presentation of MINOS, the computer algorithm used in GEM. Dr. Healy indicated that MINOS was basically designed to solve complex problems using sophisticated non-linear solution techniques recently developed for computer applications.

The second day of the workship began with remarks from the discussants. Dr. Ginn made several remarks related to congestion tolls and their relationship to the presentation of the previous day. Dr. Shabman re-emphasized several issues about the manner in which navigation models process certain data: (1) the degree to which transportation rates adequately describe mode choice decisions; and (2) the degree to which traffic diversion assumptions incorporated in the models adequately reflect mode choice decisions. Dr. Bronzini discussed several issues he had previously raised including: (1) whether GEM was a prospective replacement for MEA; (2) whether GEM requires less data than other models; and (3) presentation of the network equilibrium flow algorithm as an

alternative to the equilibrium framework embodied in GEM.

The authors identified potential research to improve the models used in navigation evaluation. Dr. Antle noted that many of the issues addressed in lock evaluation also apply to deep-draft ports and that additional research is needed to suport many of the assumptions currently embodied in the models. The workshop then closed with recommendations for further research from the discussants that would improve the navigation models and management of the inland waterways.

PROCEEDINGS

The "Workshop on Economic Aanlysis of Inland Navigation and Port Projects" (workshop) convened at 8:00 A.M. in Washington, D.C. on March 15, 1984. Dr. L. H. Blakey of the Office of the Chief of Engineers opened the workshop with a brief statement on the purpose of the meeting. The workshop was designed to promote an understanding of the various navigation evaluation models that have been developed and utilized by the Corps. The workshop was not intended to be a forum to advocate any single model or methodology for use within the Corps. The workshop was intended to be a forum to provide for a better understanding of the issues encompassed in navigation modelling and the evaluation and modelling techniques that are currently available. The workshop was divided into three sections: (1) presentations by a panel of discussants; (2) presentations by authors of four papers on navigation modelling; and (3) conclusions of the presentations and recommendations for further research and development in navigation modelling and evaluation.

The panel of paper discussants and invited experts consisted of Dr. J. Royce Ginn, Dr. Leonard Shabman and Dr. Michael Bronzini. The first discussant, Dr. Ginn, primarily discussed the GEM I and GEM II papers. He made four major points with respect to the GEM papers. First,he noted that the hourly cost of lock delay is constant in the model, although this cost will differ by commodity type. However, he also noted that one of the extensions of the model noted in GEM II allow for different costs of delay by commodity type. Second, he noted that the lock delay functions used in GEM I and GEM II relate delays to the

tonnage through the lock, although it is generally recognized that this relationship should also reflect factors such as the distribution of commodity types and tow sizes. Third, he noted that the models do not encompass the possibility of alternative waterway routes. Finally, he raised the problem of the divisibility of the last (marginal) movement estimated to use the waterway. He cited two important issues related to the "marginal movement" problem: (1) it is not important in terms of estimating benefits; and (2) indivisibility of the "marginal" movement is easily handled by GEM II.

Dr. Ginn was favorably disposed with the model structure of GEM II. He regarded GEM II as a powerful tool for the systemic problems it was intended to address. Dr. Ginn noted two problems, however, which while not specific to GEM II, become much more apparent within the framework of GEM II. First is an empirical problem relating waterway rates to lock delays within a systems framework characterized by different commodities and tow costs. Second, the existing evaluation models measure the upper bounds of system benefits because they do not model prospective changes in future parameters that determine the level of system benefits.

With respect to the Systems Evaluation paper Dr. Ginn noted that the assumptions of the model were valid. The TCM and MEA are more oriented to the incorporation of supply-side characteristics in contrast to GEM I or GEM II. He noted that a particular strength of the Systems Evaluation paper is the description of the evolutionary nature of model construction. The Systems Evaluation paper illustrates the problems

encountered in the development of the TCM and MEA models and the extensive effort necessary to calibrate these models. In this regard the Systems Evaluation paper represents not only a model for use in navigation evaluation, but also a primer on the application of computer models to complex evaluations.

The second panelist, Dr. Shabman, focused primarily on the degree to which the navigation models were consistent with the Principles and Guidelines (P&G) and economic theory. He made several general comments about the lack of clarity, completeness, sources of data, and the economic foundations of each model. He noted that both models were oriented to systems analysis and lock congestion. Dr. Shabman expressed that there was insufficient economic distinction between the two models on an abstract level. He noted that the Systems Evaluation paper did not address the prospect of alternative operating rules. He assumed, however, that this could easily be incorporated into the model.

Dr. Shabman raised two questions not related specifically to either model, in relation to the P&G: (1) Do the procedures for benefit estimation conform to P&G?; and (2) Do the tonnage forecasts conform to the P&G? With respect to the first question he noted that none of the models adequately reflected potential shifts in origins and destinations. With respect to the second question, he noted that more than rate savings is involved in determining modal split and waterway traffic. Dr. Shabman questioned the ability of the models to incorporate elements of logistics in addition to transportation rates.

With respect to economic theory incorporated in the models, Dr. Shabman

made two important points. First, was whether the navigation models accurately measured and captured the impacts of lock delays. Two issues specifically cited were the assumption that except for traffic diversion there is assumed to be no response to lock congestion and the absence of incorporating seasonality effects of navigation into the models. Second, he raised the issue of the underlying theoretical foundations of the demand function for water transportation embodied in the models. Dr. Shabman indicated that while these may not be major problems within the models, the exposition of the models required clarification and explanation of these two important issues. He summarized his remarks by noting that he viewed the navigation models as accounting devices and that he was satisfied that the models were oriented to the correct issues. He did have some concerns, however, about the conceptual foundations of the data and economic theory of the models.

The third discussant, Dr. Bronzini, began his presentation with a brief historical overview of the evolution of navigation modelling. He began with the work undertaken in the 1960's at The Pensylvania State University on lock systems capacity. He noted that a particular problem with these early efforts was the lack of any economic content in the models. He suggested that an attempt to merge the TCM and GEM was an interesting concept although due to his personal biases he was somewhat reluctant to recommend this avenue of research. Dr. Bronzini was involved in the development of the original Flotilla Model, which was subsequently modified into the TCM. Consequently, he devoted considerable attention to the validity of certain concepts incorporated

in the TCM. His discussion focused on the use of optimum tow sizes, of adjustment factors in the model which are difficult to justify, and that TCM does not appear to fully exploit what is known about network and congestion theory. Dr. Bronzini was explicit that his comments and questions should be viewed within the evolutionary context of model development and both directions for the future, as well as criticisms of past efforts.

Dr. Bronzini then discussed GEM I and GEM II papers stating that the papers were not oriented to non-mathematicians. He disagreed with one of the Lemma expressions in the paper and stated that an essay was needed on why GEM was developed which should focus on an intuitive proof that eschewed complex mathematics. He concluded his remarks by stating that he believed a better solution methodology than GEM was available that utilized equilibrium trip assignment and network equilibrium theory.

The second segement of the workshop opened with a presentation by Dr. Antle. He noted that congestion is becoming a major problem on the waterway system and that the National Waterways Study indicated that between 150 to 200 locks would be candidates for rehabilitation by the year 2000. Due to significance of lock congestion and delay reduction benefits in evaluating the feasibility of navigation projects he cited five areas that required additional efforts to arrive at a complete specification of lock delays: (1) absence of data on extreme values of lock delay; (2) improved specification of the logical process of lock delay impacts; (3) improved data base for analyzing lock

congestion impacts; (4) relationship between lock congestion and logistics cost factors; and (5) assessment of the demand price elasticity of waterway users. Additional efforts in these areas would provide not only a better understanding of lock congestion impacts, but would also provide a basis for the incorporation of additional economic feedback within evaluation models.

Ron Keeney made a general presentation on the TCM and a more detailed presentation of the MEA. He noted that the development of the TCM/MEA reflected a belief that there were significant supply-side factors such as tow sizes that had to be incorporated into the modelling effort if the models were to adequately reflect the impacts of lock congestion. The supply-side orientation was needed to have the models reflect how tow costs would change in response to changes in waterway traffic which will result from traffic diversions. Keeney stated that the TCM is an analytically based fleet sizing and costing model and not a simulation model. It computes point-to-point barge costs based on efficient tow sizes and inventory holding costs in-transit which are then adjusted to reflect waterway rates. He explained the details of the TCM and the overall theoretical framework of the TCM and its linkage to the MEA.

The need for the MEA results from the fact that the TCM does not incorporate equilibrium traffic flows. The TCM only computes barge costs which need to be translated into either positive or negative transportation rates savings depending on the levels of lock delays and rates of other modes of transportation. The MEA examines

the estimated rate savings and diverts some (or all) traffic with a negative rates savings, yielding a lower bounded estimate of system traffic. The TCM then recomputes tow costs based on new traffic levels (ex-diversion) and determines rates savings for all movements. This iterative process continues until any movement forecasted to continue using the waterway has positive or zero rates savings and any traffic projected to divert from the waterway has negative rate savings at the estimated levels of lock congestion implied by the forecasted traffic that continues to use the waterway. Keeney noted this iterative process can be slow and methodical, although it does incorporate the response of the towing industry to lock congestion. The iterative process of searching for an equilibrium between individual movements and congestion impacts is also based on the intuitive judgement of the analyst embodying traffic diversion decisions.

Mr. Sweeney's presentation detailed the rationale for the development of GEM with only a very general discussion of the nature of GEM. He noted that prior to 1978 and the modelling efforts of ORD, navigation models were generally based on single locks, even though multi-lock simulation models were available at that time. He stated that the development of GEM was the result of six major problems that characterize simulation models: (1) lack of statistics; (2) extensive calibration problems, particularly with respect to the implications of calibration on future estimates; (3) lack of economics and generally cannot incorporate estimates of a social optimum;

(4) results are generally unverifiable and it is difficult to determine the specific parameters that cause any particular result; (5) require a substantial amount of data and usually a large amount of manipulation of this data; and (6) the models are quite unwieldly.

Mr. Sweeney concluded his presentation with a hypothetical example showing how benefit estimates from a single lock model diverge from a systems model, particularly when evaluating the use of congestion tolls or non-structural measures compared to new investments.

The session concluded with a presentation by Dr. Healy on the use of MINOS in GEM. Due to the non-linear formulation of navigation problems, sophisticated solution techniques are required. Dr. Healy explained non-linear solution techniques and how these are incorporated into MINOS to provide for an efficient solution algorithm for the types of non-linear problems that can be represented by navigation evaluations. He also indicated how the particular problem formulation in MINOS provides several useful auxilliary pieces of data such as Lagrangians, which indicate the implicit costs of each constraint in the GEM. A more detailed exposition of MINOS is presented in GEM II.

The concluding workshop session began with opening remarks from the discussants, followed by a general discussion on the models that had been presented and prospective areas for future research on congestion. The session focused on four issues that had been previously presented by the discussants: (1) incorporation of logisitics costs into the rate savings parameters used the models; (2) relationship between optimal congestion tolls and their specification in the models; (3) whether the

sophistication incorporated in GEM and MINOS can be obtained using a simpler solution methodology based on equilibrium trip assignment; and (4) relationship between the specification of delay functions in the models and the economic penalties associated with lock congestion.

The workshop was concluded with a presentation by Dr. Antle and discussion of recommendations from the discussants on future areas of research. Dr. Antle noted that while most of the workshop had been devoted to inland waterways, the evaluation of deep-draft ports required an assessment of many of the same issues such as competitive impacts, financial and economic analyses, and alternatives analysis. He noted several areas for future research in lock congestion in conjunction with the discussants. These recommendations are discussed in the next section. The workshop was officially adjourned at 11:30 A.M. on March 16, 1984.

III. DISCUSSION OF FUTURE RESEARCH IMPLICATIONS

A variety of recommendations for future research on the impacts and responses to lock congestion were made at the workshop. Dr. Antle noted in his closing remarks that reduction of lock congestion has important economic implications on lock rehabilitation and replacement. Relatively little research on waterway congestion impacts and responses has been conducted, however. As a result, assumptions about responses to congestion exist. Dr. Antle suggested the following future research priorities: (1) development of theoretical foundations and a data base to support assumptions about responses to congestion; and (2) development of a systematic data base detailing (a) delay functions and parameters, (b) towing response to lock congestion, (c) shipper response to lock congestion. To provide for an efficient congestion research program, he also recommended that the following preliminary steps be undertaken: (1) prepare a draft report and users manual for the TCM; (2) prepare a draft report and users manual on the GEM; and (3) prioritize research efforts in relation to evaluation needs.

Each of the discussants also identified areas that they felt were the most important research topics to be immediately addressed. Dr. Ginn stated that probably the most important area was the development of a justification of delay costs and the impact on modal split. This would include both shipper and carrier responses. It would require interaction with shippers and carriers to develop a data base. Dr. Bronzini noted

that probably the least defensible aspect of Corps studies is the commodity forecasts, although this is an issue somewhat broader than the analysis of lock congestion. However, he noted three important research areas for further study: (1) improvement in vessel operating costs; (2) better description of modal split parameters; and (3) examination of the relationship between traffic levels and direct environmental impacts. Dr. Shabman also noted three areas for additional research efforts: (1) assessment of strategic versus tactical specification of modal split (i.e. model equilibrium versus operating practices); (2) better specification of the delay process; and (3) assessment of lock congestion and various systems management alternatives.

Based on suggestions by workshop participants, there are seven topical areas of research related to lock congestion and navigation modelling that should be pursued in the near future. These are:

(1) Development of a theoretical foundation for lock congestion impacts and responses. Consequently, its theoretical foundations are difficult to describe in a general manner. However, additional work is needed in this area to provide a structured framework suitable for empirical testing of the importance of different hypotheses relative to lock congestion. Lock congestion can have a wide variety of prospective effects on both carriers and shippers. The development of a theoretical foundation will allow for empirical testing of certain hypotheses on the relative importance of congestion impacts, behavior and modal split.

(2) Development of a data base on towing industry responses to lock congestion. Current modelling capabilities generally reflect unsupported assumptions which allow for limited response of the towing industry to lock congestion. Although these assumpitons may be intuitively correct, they have no underlying empirical documentation. A data base on towing industry responses to lock congestion should be developed that would allow for empirical testing of the relative

importance of the various responses to lock congestion available to the towing industry.

(3) Development of a data base on shipper responses to lock congestion. Existing navigation models allow limited responses to lock congestion by waterway shippers. The primary response is assumed to be higher waterway rates as a result of increased congestion or diversion to an alternative route or mode. However, the price of increased congestion may not uniformly reflect actual lock delays. Shippers may respond to offset portions of congestion costs or they may incur additional logistics or production costs as a result of congestion. Prospective responses will likely differ by commodity and industry.

(4) Development of a better specification of modal split as it relates to waterway shipments based on the results of the three topics cited above. This would include an asseessment and ranking of such factors as route and mode choice, origin-destination shifts, potential impacts on production levels, logistics cost impacts, costs of risk associated with lock congestion, and strategic and tactical locational advantages of the waterway.

(5) A reassessment of the lock delay process in relation to the results of topics (2) and (3) and a specification of the lock delay function. Current models generally limit congestion impacts to the demandside. However, shipper or carrier responses that alter tow size, tons per tow, back-haul relationships or tow speed parameters would impact estimates of lock capacity.

(6) Investigate the feasibility of merging the TCM with GEM. At an abstract level this appears feasible and would combine a powerful costing model with equilibrium solution. However, it is necessary to evaluate the assumptions of each model to ensure their compatibility.

(7) Investigate the feasibility of various waterway systems management strategies based on the results of the previous research topics. This would include topics such as congestion tolls, lock scheduling and optimal timing of lock rehabilitation, replacement and maintenance.

Four additional research areas which were cited by the discussants could potentially include the following topical areas: (1) specification of towing industry costs; (2) level of necessary model detail for exogenous factors such as seasonality; (3) traffic projections under with or without conditions; and (4) specifications of the relationship between traffic levels and direct enviornmental impacts. Although these are important topics, development of a research plan to address these issues will be predicated on the results of the seven primary research areas cited above.

PART II

PAPERS PRESENTED AT MEETING

An Overview of Waterway Systems Analysis Capability and Problems*

The national waterway system constructed and managed by the Corps of Engineers has reached the evolutionary stage where few waterway extensions are likely. One of the major investment problems now is that of capacity expansion or perhaps, in the economic short run, one of managing available capacity. The inland system now approaches 11,000 miles, with navigable depths 9 feet or greater, particularly achieved by the over 250 existing locks. This system currently moves over 500 million tons of traffic annually. Projections indicate increases of about 50% by the year 2000, although traffic growth greatly exceeded this rate of increase from the period 1947 to 1978. Total inland waterways barge traffic has shown no growth during the past five years but some waterways do show recent growth. Increasing traffic brings additional congestion at some of the locks and in some of the channels, thus increasing the costs to waterway shippers.

Recent studies of the waterway systems suggest that 28 locks will have traffic levels which approach their estimated physical capacity and thus would likely be the source of substantial delays. Five of these projects are well advanced in the Corps long range budget for replacement with larger locks (Second lock at L&D 26, Oliver, Gallipolis, Inner Harbor and Bonneville Locks). For projects with capacity problems, some form of systems analysis is required, simply because some of the delays will shift to the next most limited capacity point in the system. Systems analysis estimates net savings while evaluating delay costs. Fortunately a substantial set of operating systems analysis models has been developed and experienced Corps systems analysts are utilizing the technology.

The second and perhaps more difficult problem for investment choice will come from perhaps 100 locks which are approaching their design life and where major rehabilitation or replacement will be required. The economic analysis of this kind of decision is much different from simply confronting a need to economically reduce congestion. While a system analysis is useful, the criteria for decision and the evaluation process will necessarily emphasize many factors in addition to actual or potential congestion.

What kind of analytical models and data bases do we have to perform competent investment analysis? The following section summarizes the "systems models" which are available (and in use by the Corps).

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*Lloyd G. Antle, Chief, Navigation Division, IWR

SYSTEMS MODELS

- Commodity Flow Model - CFM - (INSA)
  Uses multiregional input output model to estimate flows consistent with production, intermediate and final consumption
  Applications - DOE study of energy commodities

- Transportation Freight Model - TFM - (INSA)
  A network model which allocates flows among transport modes, based on cost and performance factors
  Applications - 1976 "User Charge Impact Study" by OCE
  DOT studies of energy utilization
  1980 Interagency Coal Study (ICS)

- Tow Cost Model - TCM - (Upgrade of INSA Flotilla Model by Huntington District) Optimizes tow movements to carry projected traffic and estimates barge costs
  Applications - Gallipolis Phase I Study
  Lower Ohio (L&D 52 and 53)
  Monongahela Study
  Oliver Study
  Cumberland

- Lock Capacity Function Generator - LOKCAP - (INSA)
  Estimates delay times for double lock chambers. Fits a hyperbolic delay function:

$$\text{Delay} = \frac{D_L \cdot Q}{C_L - Q}$$

  where D_L = delay function parameter
  C_L = daily capacity
  Q = daily traffic
  Applications - National Waterway Study
  Upper Mississippi Master Plan

- o Waterway Analyses Model - WAM - (INSA)

  This model simulates a waterway systems operation to generate estimate of delay costs, given projected traffic.

  Applications - Oliver
  Gallipolis
  Monongahela
  Lower Ohio
  Cumberland

- o Marginal Economic Analysis - MEA - (Huntington District)

  Using delay costs generated by TCM and WAM, this model generates an estimate of traffic diverted by increased delay costs. Equilibrium is found by repeated runs after analyst removes shipments which appear to have negative rate savings.

  Applications - Gallipolis
  Lower Ohio
  Monongahela
  Oliver

- o General Equilibrium Model - GEM - (St. Louis District)

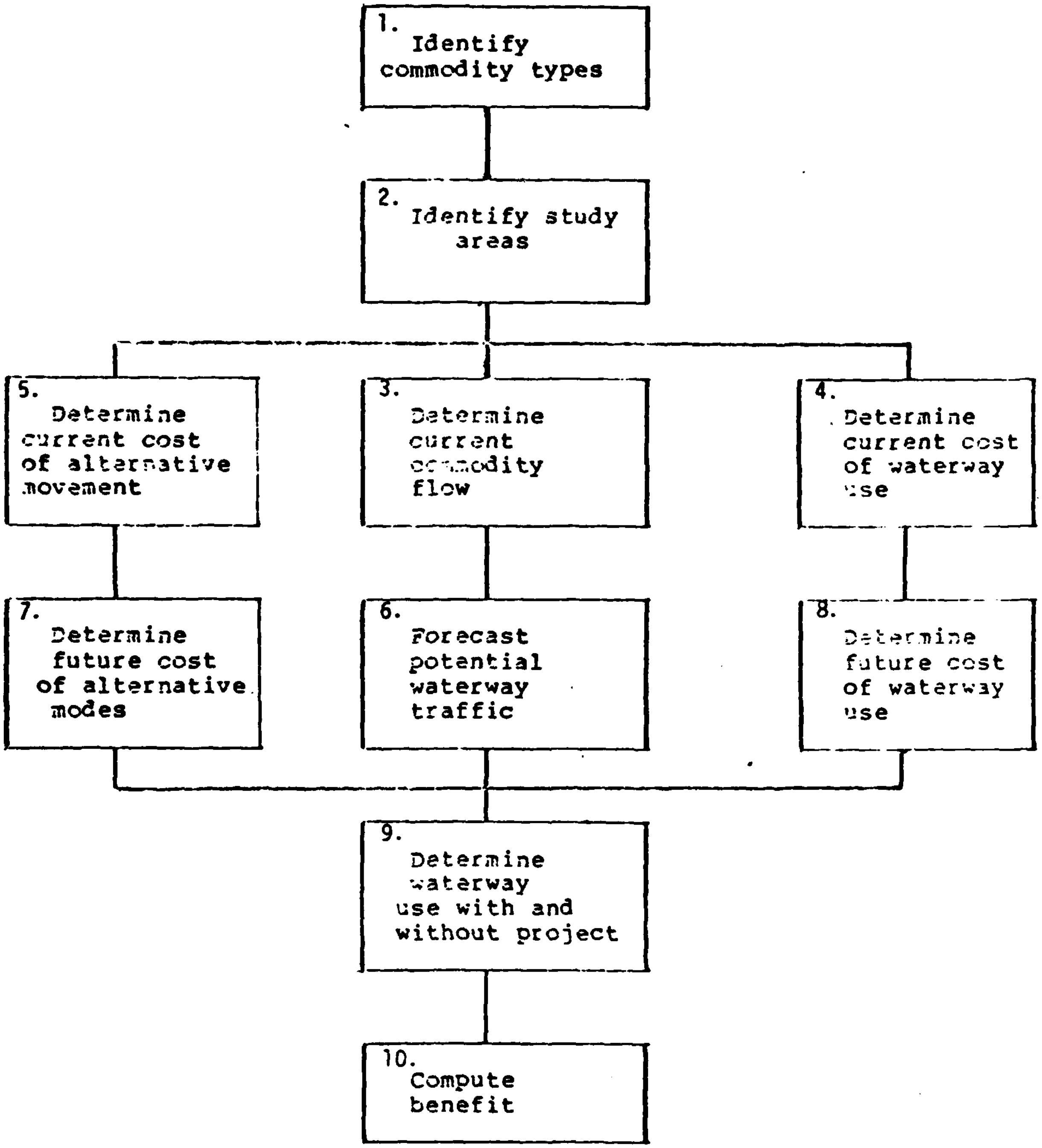
  Using traffic forecasts, delay parameters (hours delay at 50% of capacity and physical capacity) and gross rate savings, GEM directly estimates equilibrium diversions across a waterway system

  Applications - Test runs on L&D 26 and Oliver.

What are the requirements for economic analysis of waterway projects?

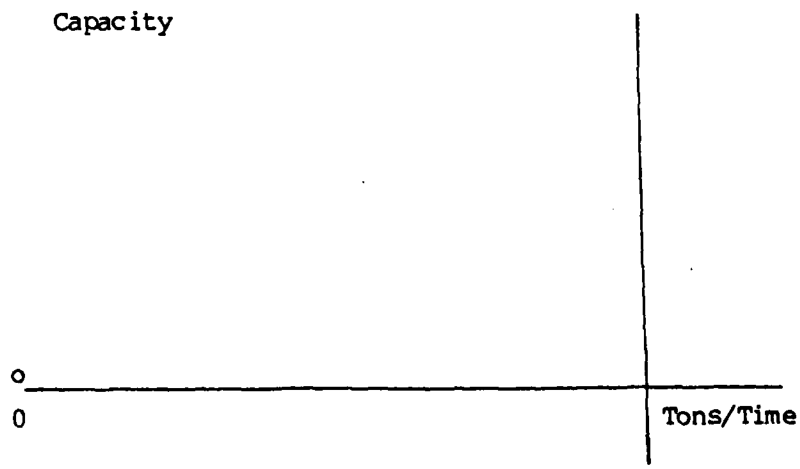
The most recent and clearest statement of the requirements on the Corps is contained in the "Economic and Environmental Principles and Guidelines for Water and Related Land Resource Implementation Studies" signed by President Reagan on 3 February 1983 and published by the Water Resources Council on 10 March 1983. Figure 1 shows a flow chart of the steps to be taken and two levels of "systems" views are indicated. Steps 3-7 develop the estimates of potential traffic, the costs of alternative modes and the current cost of waterway use. Good analysis requires a systems perspective

Figure 1


1. Identify commodity types
2. Identify study areas
5. Determine current cost of alternative movement
3. Determine current commodity flow
4. Determine current cost of waterway use
7. Determine future cost of alternative modes
6. Forecast potential waterway traffic
8. Determine future cost of waterway use
9. Determine waterway use with and without project
10. Compute benefit

to maintain a consistent set of economic and policy factors vis-a-vis water and competing transport modes. Good practice should also maintain the use of consistent data bases across various Corps studies. Steps 8 and 9 generate waterway use with and without a project, which depends on future waterway costs. An estimate of system delays with and without the project are a necessary product which requires a system analysis procedure. Finally, net benefits require an evaluation of traffic which would be diverted by the economic costs added to waterway shipments by delays. What are we talking about when we use the words capacity and congestion?

Capacity is a physical concept used in transportation studies to indicate the quantity of traffic which can utilize a facility under assumed conditions. Capacity may mean maximum, practical or any number of subjective descriptions. Capacity in Corps navigation analysis has indicated a very wide range of assumptions and conditions. For instance, the existing Lock and Dam 26 has been estimated to have a capacity of from 41 million to near 160 million tons per year. Each capacity estimate reflects set of assumptions, outlined below.

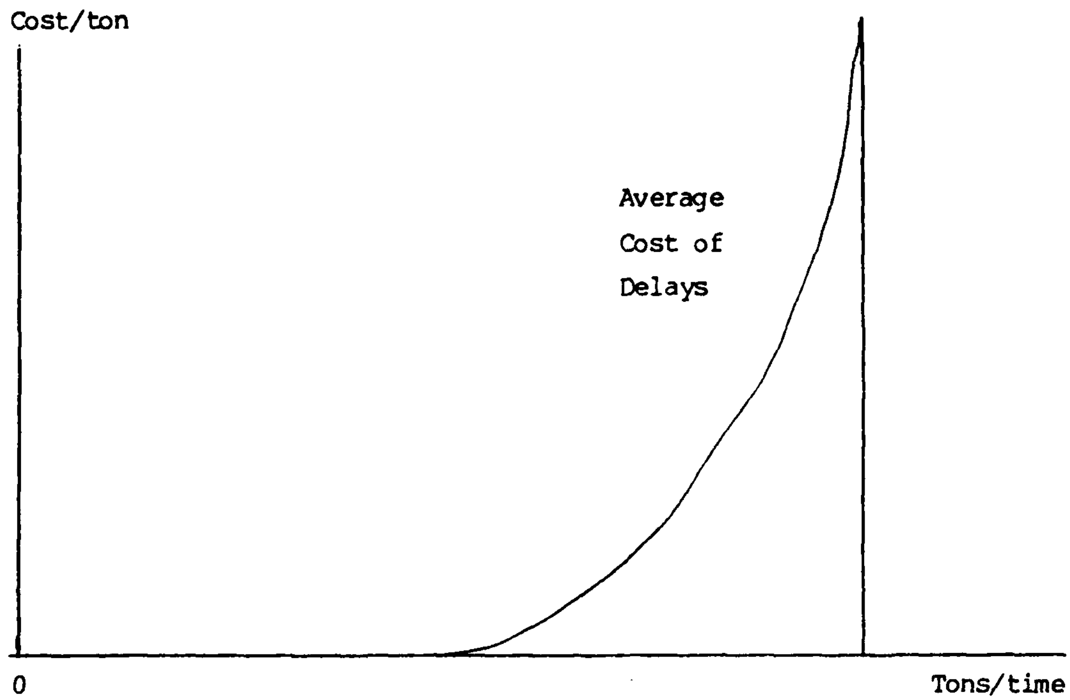


How many tons can go thru a lock in a year?

Depends on

Time Available - Percentage of time that lock is out of service due to lock repair, accidents, ice, fog, staffing, policy, etc.

Congestion is an economic measure of the value of capacity. It represents an estimate of the economic penalty of delay. As transportation levels in any transport facility increases, there are increasing delays, finally reaching a point when there is an infinite queue and infinite delay costs. At a navigation lock, waiting tows may cost $200 or more per hour. The chart below represents a delay function for a lock facility.



Congestion results from two basic conditions: (1) capacity, the upper bound, and (2) the distribution of arrivals to use the facility. If a lock can process two tows per hour and if the tows arrive exactly every 30 minutes, there will be no delay until tows arrive in a rate which exceeds two tows an hour at uniform intervals. However, if arrival is random, arrival rates of less than two tons an hour will experience some delay. The amount of delay experienced by each tow will vary, therefore the chart above represents average delay costs.

Recent Corps Studies Using Systems Analysis

Gallipolis. This is an odd ball lock size in the new highlift system on the Ohio. In addition to being undersized, it has poor downstream approach conditions. The major commodity locked is coal. The Tow Cost, Waterway

Analysis Model and Marginal Economic Analysis Models were used in the study and Contractor developed projections.

Upper Mississippi Master Plan. This study evaluated Upper Mississippi, Illinois and L&D 26, 27 resulting in a recommended authorization of second lock at L&D 26. Additional upstream projects were found to be feasible. The study used General Equilibrium Model along with simulation models and middle (baseline) projections from National Waterway Study.

Oliver. Oliver Lock is another odd ball lock size in a system of larger locks. Evaluated Tenn-Tom and Black Warrior traffic which would compete for available capacity at Demopolis and Coffeeville. The Tow Cost, Waterway Analysis and Marginal Economic Analysis Models were used along with OBERs projections.

System Analysis Problems. Most recent studies have been done using the family of simulation models some of which originated under a Corps Contract with Pennsylvania State University and further developed (or enhanced) by the INSA program and improved by users at Huntington District and the waterways simulation group at WES, headed by Larry Daggett. This approach has been used in Gallipolis, Oliver, Monongahela and Lower Ohio Studies. The basic problems with the application of the simulator approach has been (1) that some of the estimates do not seem consistent with the underlying theoretical expectations, i.e., such as benefits for a single lock being greater than benefits for the total system (Oliver in two time periods of the analysis), (2) diversion of long haul movements rather than short haul movements, (3) the demands of the simulation models for data and computer time, and (4) whether the analyst can affect equilibrium benefit estimates by the strategy for remaining (diverting) shipments.

Because of these (and perhaps other problems) Don Sweeney of St. Louis District (LMS) began development of an optimizing model (General Equilibrium Model - GEM), which seeks to minimize net system benefits by systematically

evaluating a large set of alternative diversion strategies. The model was utilized during the Upper Mississippi Master Plan Studies. The GEM simplifies the waterway system to a network of delay points, and accepts a given average tow size (and loading). The original version of the model used considerable computer time, and a good deal of effort has gone into more efficient computer utilization. Other efforts (discussed by Healy and Sweeney) have been made to transform the problem into a linear or non linear programming problem.

Whether the GEM solves more problems than it raises essentially is a challenge to continue careful testing on real projects and through critical review. Perhaps combining the Tow Cost Model with the GEM can improve its ability to project future benefits based on realistic adaptation of the towing industry and shippers to increased delay costs.

General Problems in Navigation Analysis. Calculation of the effects of delays on shippers and carriers is but one of the important challenges to Corps Navigation Analysts. I summarize some more general, and perhaps more important issues for consideration:

Excessive Variation in Projections from Project to Project
- Choice of different basic sources of forecasts
- Inconsistent assumptions
- Variety of methodological approaches

Lock/Channel Capacity
- Basis of estimates
- Projections of capacity parameters, such as number of barges per tow, loading per barge and number of empty barges.

Mode and Route Choice
- Inconsistent criteria between studies
- Variety of methodologies
  - Service (speed, dependability)
  - Transloading, fleeting, etc.

Delay Function

- Sparseness of data for high delay values

Rate Base

- Increasing difficulty to obtain rate data
  - Deregulation
  - Restriction on surveys

Diversion Analysis

- Results from systems model often difficult to rationalize

Economic Basis for Replacing/Repair of Old Locks

Evaluation of Congestion Fees/User Charges Impacts

AGENDA

Workshop on Economic Analysis of Inland Navigation and Port Projects

15-16 March 1984

Pulaski Building

THURSDAY - 15 March

0800-0815	Introduction	Dr. Blakey (CWP)
0815-1015	Panel of Invite Experts - Present their views of Problems and Successes based on review of four written presentations	Dr. Bronzini (UT) Dr. Ginn (Cambridge Systematics) Dr. Shabman (VA Tech)
1015-1045	BREAK	
1045-1130	Continue Panel 30 min. presentations by each panelist/25 min. for discussion)	
1130-1200	Review of Applications of Issues in Systems Models	Dr. Antle (IWR)
1200-1300	LUNCH	
1300-1400	The ORD Systems Analysis Strategy-State-of-the-Art (40 min. Presentation/20 min. for questions)	Mr. Keeney (ORH)
1400-1500	The General Equilibrium Model (40 min. Presentation/20 min. for questions)	Mr. Sweeney (LMS)
1500-1530	BREAK	
1530-1630	Applications of MINOS to GEM Analysis Problems	Dr. Healey (Boeing)
1630-1700	Small Group Discussion of Problems and Alternative Solutions	

FRIDAY - 16 March

0800-1000	Panel of invited experts Recap, revisions as a result of what they have learned at the Seminar (if any), etc.
1000-1030	BREAK
1030-1200	General Discussion/Recommendations

THE OHIO RIVER DIVISION'S APPROACH TO
NAVIGATION SYSTEMS ANALYSIS

Presented by Ron Keeney

Good afternoon. I am Ron Keeney of the Huntington District. I am representing one of two navigation support centers which have been established in the Ohio River Division. The other center is located in the Louisville District and is represented here today by Dave Weyer.

I'd like to thank Dr. Antle and his staff for inviting us to attend and participate in this important workshop on navigation economic analysis. The existence of the two navigation centers, I think signifies ORD's commitment to systems analysis for formulating sound waterway investment plans. Collectively, the centers are responsible for all facets of our navigation systems analysis program beginning with the development of consistent data bases and concluding with the development and application of systems models.

#1 PURPOSE

My purpose today is to give you an overview of the models which we are currently using to estimate project benefits. Of equal or greater importance, of course, is the economic and other data that are input to the models such as traffic projections and transportation rates. I understand that in

later technical sessions we will be discussion these items. So I won't go into much detail here.

Before getting into the model itself, I'd like to briefly discuss the conceptual framework for inland navigation benefit studies and why systems analysis techniques are required.

#2
GRAPH

This slide graphically depicts the analytic framework. Although the curve shapes are oversimplified, the graph expresses the supply and demand for waterway use as a function of tonnage (x axis) and the price per unit of output (y axis). The demand curve represents the willingness of users to pay for use of the waterway system as measured by the transportation savings they enjoy over the least-costly overland mode. The curve is constructed by arraying all existing and projected movements from highest-to-lowest unit savings and accumulating the tonnage across the x axis. The average towing cost (ATC) curve represents the corresponding costs that shippers would have to pay for use of the waterway system. The marginal towing cost curve represents the true marginal cost for each movement including the effect of increased delays on system users and/or possible effects on backhaul relationships. Definition of this curve is important for evaluation of lock congestion fees and I'll say more about how we estimate it later on.

Using this conceptual model, we can see that the rational shipper would not choose to increase their use of the system beyond traffic level Q_1. Movements beyond this point would result in the costs for water shipment exceeding the unit rate savings, meaning that it would be cheaper to move by an alternative mode. So, we refer to traffic level Q_1 as the equilibrium level of system use.

#3
GRAPH

Once we've determined the equilibrium for the existing system, we then need to estimate what the <u>new equilibrium</u> would be for the system with an improvement at the project under study. Conceptually, we construct, ATC_2 reflecting the lower shipping costs on the system as a result of the improvement. The economic benefits for the improvement are then computed as the increase in system rate savings as a result of the lower shipping costs (shaded area).

#4
WHY SYSTEMS
ANALYSIS

<u>Application of systems</u> analysis techniques is required to define these cost-benefit relationships and the equilibrium traffic level because of the interdependence of traffic flows among the many projects that go into making up a waterway system. Other system projects can restrict traffic flows at the project under study and prevent the materialization of the expected benefits. At the same time, the additional traffic allowed to move because of improvements at individual projects may increase delays at other projects in the system and thereby reduce the savings for other movements. So, we

have possible effects flowing from the project to the system as well as from the system to project that can affect equilibrium traffic levels and benefits. These considerations clearly dictate the need for use of system analysis techniques which take these interractions into account in estimating the benefits for individual project improvements.

#5 GRAPH

Now, how do we define all of these variables and relationships, not only for existing traffic, but for future traffic levels as well? We have complete transportation rate and cost information for all existing Ohio River system movements as well as future traffic demand forecasts. Using these two data bases both of which are origin-destination and

#6 GRAPH

commodity specific, we can construct demand curves for each decade over the period of analysis. All that remains then is a method for computing barge shipping costs in each decade over the period of analysis for each O-D commodity movement with and without specific project improvements and the corresponding equilibrium traffic levels.

The model that we use to keep track of all the traffic interactions and to compute barge line-haul costs in each future year is the Tow Cost Model (TCM). A Marginal Economic Analysis Model (MEA) which is designed for iterative use with the TCM is then applied to determine equilibrium traffic levels and system rate savings in each decade. I'll discuss the TCM first followed by the MEA.

#7 TCM OVERVIEW

The TCM is a modified and expanded version of the original Flotilla Model which was conceived as part of the Corps' INSA Program and provided to the field for use. The model is an analytically-based fleet sizing and costing program; not a simulation model. The basic function of the model is to compute the barge line-haul costs for all port-to-port traffic demands on any given waterway system with defined characteristics.

#8 TCM ORGANIZATION

The cost calculations are made using a set of computer programs and detailed input data that describes (1) the waterway system being evaluated; (2) the equipment used for towing operations and the costs to industry for owning and operating the equipment; and (3) the port-to-port commodity flow demands. Using these data, the model calculates the resources required for each port-to-port movement (number of barges and towboats, fuel, etc.) and the associated barge line-haul costs. In addition to providing detailed output data on each movement the model also provides a variety of other more general cost analysis and equipment requirement reports. The effects of imposing various user charge mechanisms for recovery of Federal costs can also be conveniently evaluated using the model. Four cost recovery mechanisms are available including (1) fuel tax; (2) lockage fee; (3) segment tolls on a ton-mile basis; and (4) barge and towboat registration fees.

#9
ALGORITHM

The heart of the TCM is the port-to-port algorithm which computes the time and cost for each port-to-port commodity movement. The algorithm determines (subject to user specified constraints) the most cost-effective tow size for each port-to-port commodity movement by cycling through the time and costs for all possible shipping plans and allowable tow sizes. The algorithm is not a specific equation or set of routines; rather it is the overall logical framework through which the model works. For each port-to-port movement, the algorithm calculates the round-trip time and costs for the logical combination of events needed to move the tow from the shipping port to the receiving port including the effect of backhauls and refleeting enroute. The major time elements include:

(1) Time spent loading/unloading barges;

(2) Time loaded barges spend awaiting towboat;

(3) Time spent in making/breaking tows;

(4) Tow transit time -- Open River;

(5) Lockage time;

(6) Lock delay;

(7) Time spent in refleeting operations.

These times are then translated into the costs of transport by applying the equipment operating cost per unit of time.

#10 SYSTEM INPUT

The input data necessary to run the model is fairly large. The first major item is a description of the waterway system being analyzed. As in most transportation models, the system is represented in network fashion with ports, locks, river junctions and refleeting points represented as nodes with connecting waterway links or segments between them. For each river segment, we specify the length, minimum and average depth and the average channel velocity. The minimum depth is used for computing barge loadings. The average depth and channel velocity are used by an imbedded equation to calculate tow speeds in the segment. This, along with the segment length, determines the total tow transit time in each segment and, of course, miles traveled.

#11 DELAY FUNCTION

For each lock in the system, we have to specify its location, capacity, lockage time and a delay function. The capacity and lockage time estimates are based upon the LOCALC Model. The delay function is generated internally in Tow Cost using a simple hyperbolic formula. The formula, $W = \frac{K}{C/X-1}$, expresses the average delay per tow as a function of the physical capacity of the lock (c), the delay at 50% of capacity (k), and the utilization rate (x). The values for (k) at each lock are determined using actual delay observations and regression analysis.

I would add that a more sophisticated procedure has been developed for computing lock delays. This procedure involves

the iterative use of the TCM and a modified version of the Waterway Analysis Model (WAM). The TCM generated fleet is input to the WAM in order to provide detailed simulation of the associated lock delays. The WAM generated delays are then fed back through the TCM to recompute the fleet requirements and the line-haul costs. This procedure has the advantage of more accurately measuring the delay effects of changing tow size over time as well as providing delay observations at very high levels of utilization which are not normally available with analytic procedures.

The other items of the system description are fairly self explanatory and include the barge loading, unloading and fleeting times in port as well as the time required for refleeting barges at the designated refleeting points. All of these times are averages based upon our in-house shipper surveys.

#12
EQUIPMENT
INPUT

The next major input item is the towing equipment descriptions. These data describe the physical dimensions, capacity, fixed and variable operating costs and other related information for the towboats and barges to be considered by the model.

#13
COMMODITY
INPUT

The next item is the commodity shipment list which describes the commodity being moved, the origin and destination port, the annual tonnage and the percentage of the tonnage

moved in dedicated equipment. The dedicated equipment factor is determined based upon detailed analysis of the loaded and empty barge flows at each lock using our PMS data base as well as the barge flows reported to our Waterborne Commerce Statistical Center in New Orleans.

#14
TRANS
CLASS

The last major input item is the assignment of each of the major commodity groups being used in the analysis to a separate transportation class. This is done in order to keep a separate accounting of the transportation costs for each commodity for later use by the MEA. For each transportation class we also assign a handling class which determines the barge loading and unloading times in port, a value per ton which is used along with an inventory holding cost factor to compute the inventory holding cost while the commodities are in transit, and finally the barge type for each movement.

#15
MODEL OUTPUT

As I stated earlier, model output provides various hard copy reports which summarize the model results. Reports that are available include:

(1) Annual Towboat Utilization and Costs
(2) Annual Barge Utilization and Costs
(3) Tow Size Distribution on all Segments
(4) Lock Utilization
(5) Lock Costs

(6) Port Utilization

(7) Port Costs

(8) Segment Cost Summaries

(9) User Charge Summary

However, the primary output is a file which contains all of the port-to-port commodity movements and a detailed breakdown of the costs.

#16 MODEL CALIBRATION

Prior to using the TCM for actual production runs, we go through a calibration effort to insure that the barges and towboats being selected by the model and the loadings approximate what the shippers are actually doing. This is done by comparing model output to observed PMS data at selected projects. The variables we look at are:

(1) Tow and barge loadings by class;

(2) Number loaded, empty, and total barges by class;

(3) Towboat size distribution;

(4) Tow speeds by waterway;

(5) Lock delays.

Variables that are available to us for refining the equipment selection are minimum channel depth which determine barge loadings, tow size limitations on waterway sectors, and other variables. Once the model is calibrated, we compute

the barge line-haul costs for all port-to-port movements in our base year shipment list and store the results for later use by the Marginal Economic Analysis (MEA) Model.

#17 MEA

That pretty well wraps up my discussion on the TCM. Now to the Marginal Economic Analysis Model (MEA). The basic function of the MEA is to compute the change between the base year and future year modeled costs for each port-to-port movement as provided by the TCM and to determine the corresponding effects on the rate savings for each movement.

Thus, the model input includes the TCM output from the base year run and each future year run as well as a transportation rate matrix for the base year. The transportation rate matrix is developed using conventional transportation rate surveys and serves to keep our analysis "rate-based" as required by the P&G. The matrix contains the (1) existing barge line-haul rate per ton, (2) existing total water-routing cost/ton, and (3) the least costly overland rate/ton.

For each run of the TCM, the MEA simply computes the change in modeled costs for each movement and makes corresponding adjustments to the existing barge line-haul rate in the matrix. The revised line-haul rates are then added to the other fixed components of the water-routing cost stored in the matrix to yield a revised total water-routing cost for each movement.

The revised total cost for each movement is then compared with the base overland rate to determine the revised rate savings. The MEA then ranks all of the movements in the input shipment list from highest-to-lowest unit savings and provides running totals for system tonnage, ton-miles, total water-routing costs and total system rate savings. Similar rankings are provided for the subset of system traffic that transits any desired lock.

#18 MEA PRINTOUT

As our analysis progresses over time, increased traffic demands and the associated congestion results in many of the waterway movements becoming uneconomic which means that the traffic demands exceed the equilibrium level which we defined earlier. Since project benefits are computed as the difference between "with" and "without" project system rate savings at the equilibrium level, the uneconomic movements must be carefully diverted until the equilibrium solution is achieved. Since the uneconomic movements impact the efficiency of all other movements with common routings, it is necessary to delete the movements from the input shipment list in small increments and repeat the entire modeling process after each diversion. The movements are selected for diversion in rank order from highest-to-lowest dis-savings. This iterative diversion process is continued until the system traffic level is reached at which all movements show a positive savings.

#19 DIVISION PROCEDURE

Because of the very complicated competitive relationships of traffic movements in large systems, we recognize that this process produces an initial estimate of the equilibrium. There is some danger that traffic could be overdiverted (give example). In order to test for this possibility, we develop a shipment list containing all of the diverted movements and synthetically set the delays at all of the system locks at the level implied by our initial equilibrium solution. The model is then rerun to determine if any of the diverted movements would be economic at these delay levels. If economic movements are identified, they are then added to the shipment list from our initial equilibrium solution and the model is rerun to determine if the addition of those movements created other uneconomic movements. If so, the same diversion process is followed until a *new equilibrium* solution is obtained.

#20
PROJECT
BENEFITS

This process is used to define equilibrium traffic levels for each decadal traffic projection and each project change being evaluated. By varying the model input parameters such as lock capacity and lockage time one at a time to reflect these movements, we can construct a time series of total system rate savings with and without the improvements. The project economic benefits are then computed as the incremental increase in system savings in each time period.

The benefits for a lock congestion fee can also be evaluated by simply diverting additional increments of traffic beyond the equilibrium level until the point is reached at which total system rate savings are maximized. This is acheived where MTC = MRS.

#21
IMPACTS

In addition to providing project benefits, the model provides sufficient data to describe the impacts of the project on:

(1) Total System Traffic
(2) Traffic at all System Projects
(3) System Lock Delays
(4) Delays at all System Projects
(5) Traffic Diverted to Overland Modes
(6) Other Variables

#22
SENSITIVITY
TESTS

Sensitivity tests can also be easily performed to evaluate the effects of:

(1) Alternative Traffic Demands
(2) Changes in Overland Rates
(3) Changes in Barge Rates
(4) Changes in Fuel Prices
(5) Lock Improvements Elsewhere in System
(6) User Charge Recovery

That concludes my presentation. In summary. I would like to say that we view one of the strengths of the model to be its flexibility in analyzing a wide range of navigation problems. We have the capability to analyze not only the effects of structural and nonstructural lock improvements and user charges, but many other issues as well, including:

(1) Channel Deepening

(2) Channel Widening

(3) Port Improvements

(4) Long Term Changes in Fleet Composition

(5) Others

OVERVIEW

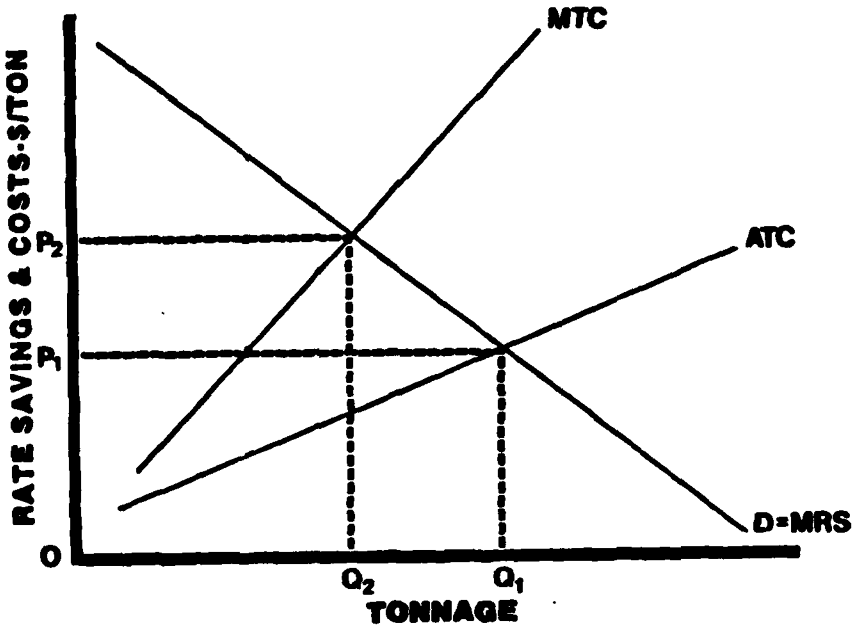
OHIO RIVER DIVISION

NAVIGATION ECONOMIC ANALYSIS

METHODS AND MODELS

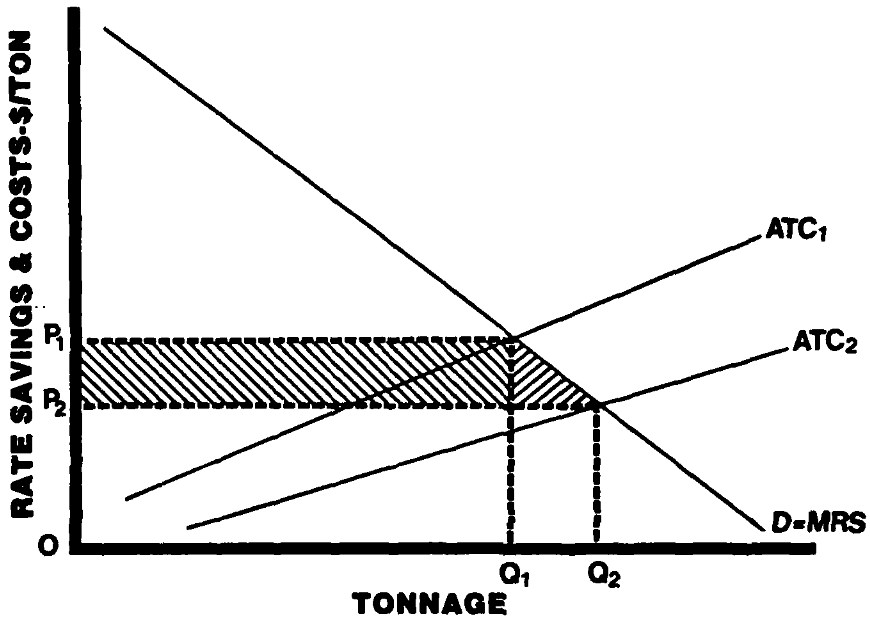
SLIDE # 1

WATERWAY ECONOMIC ANALYSIS



SLIDE # 2

SYSTEM BENEFITS FOR LOCK IMPROVEMENT



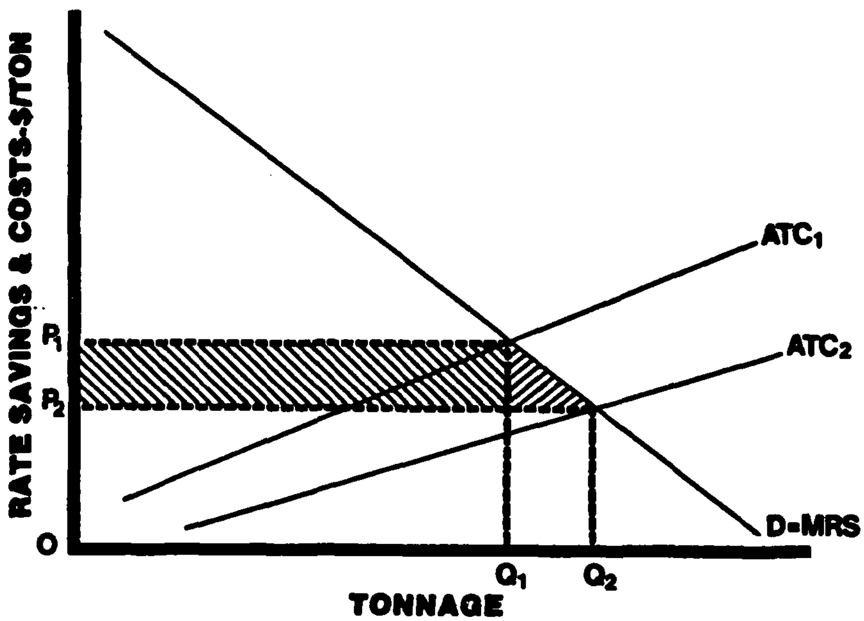
SLIDE # 3

WHY SYSTEMS ANALYSIS?

- DEFINE IMPACTS OF PROJECT ON SYSTEM
- DEFINE IMPACTS OF SYSTEM ON PROJECT
- ESTIMATE INCREMENTAL PROJECT BENEFITS

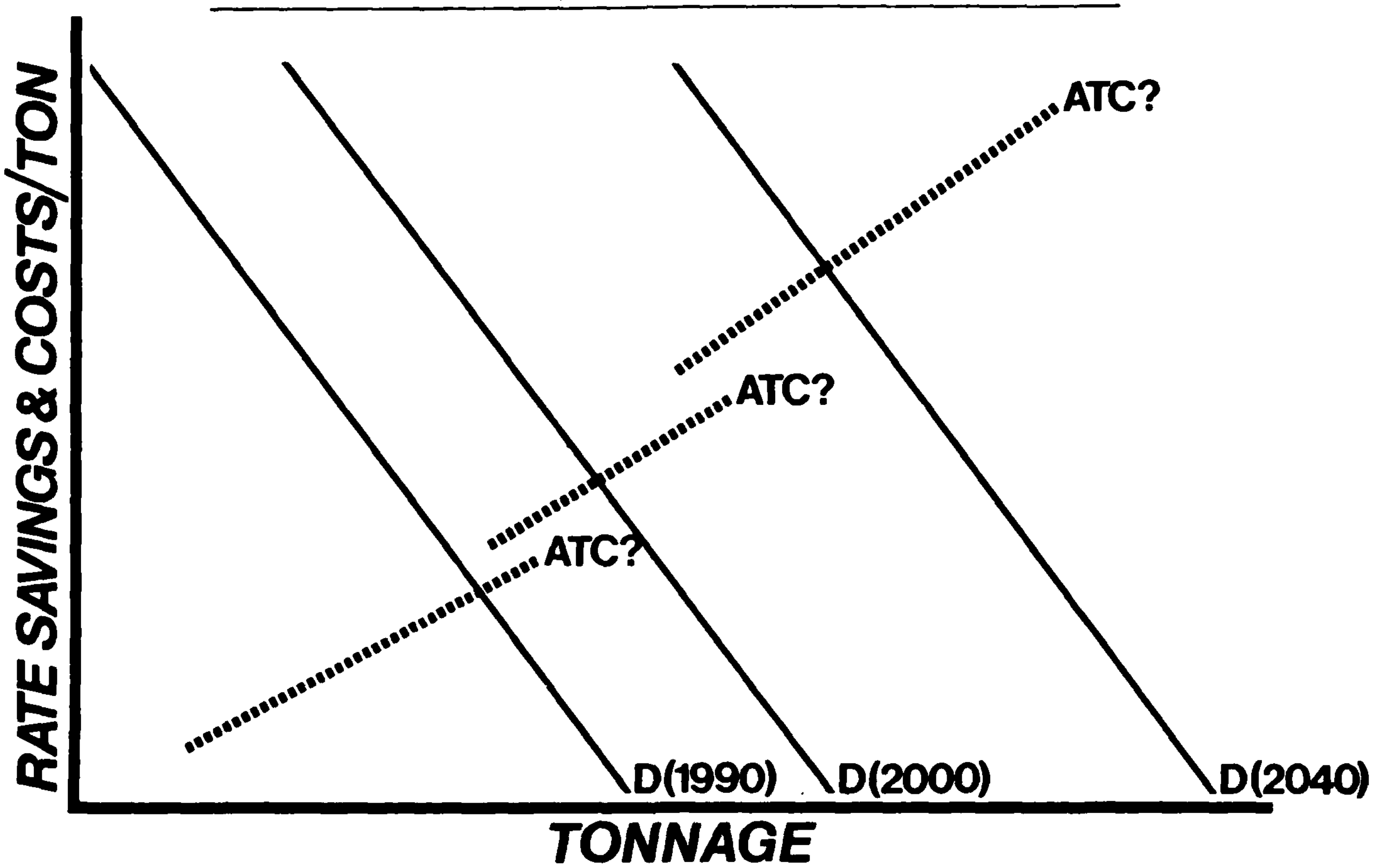
SLIDE # 4

SYSTEM BENEFITS FOR LOCK IMPROVEMENT



SLIDE # 5

WATERWAY ECONOMIC ANALYSIS

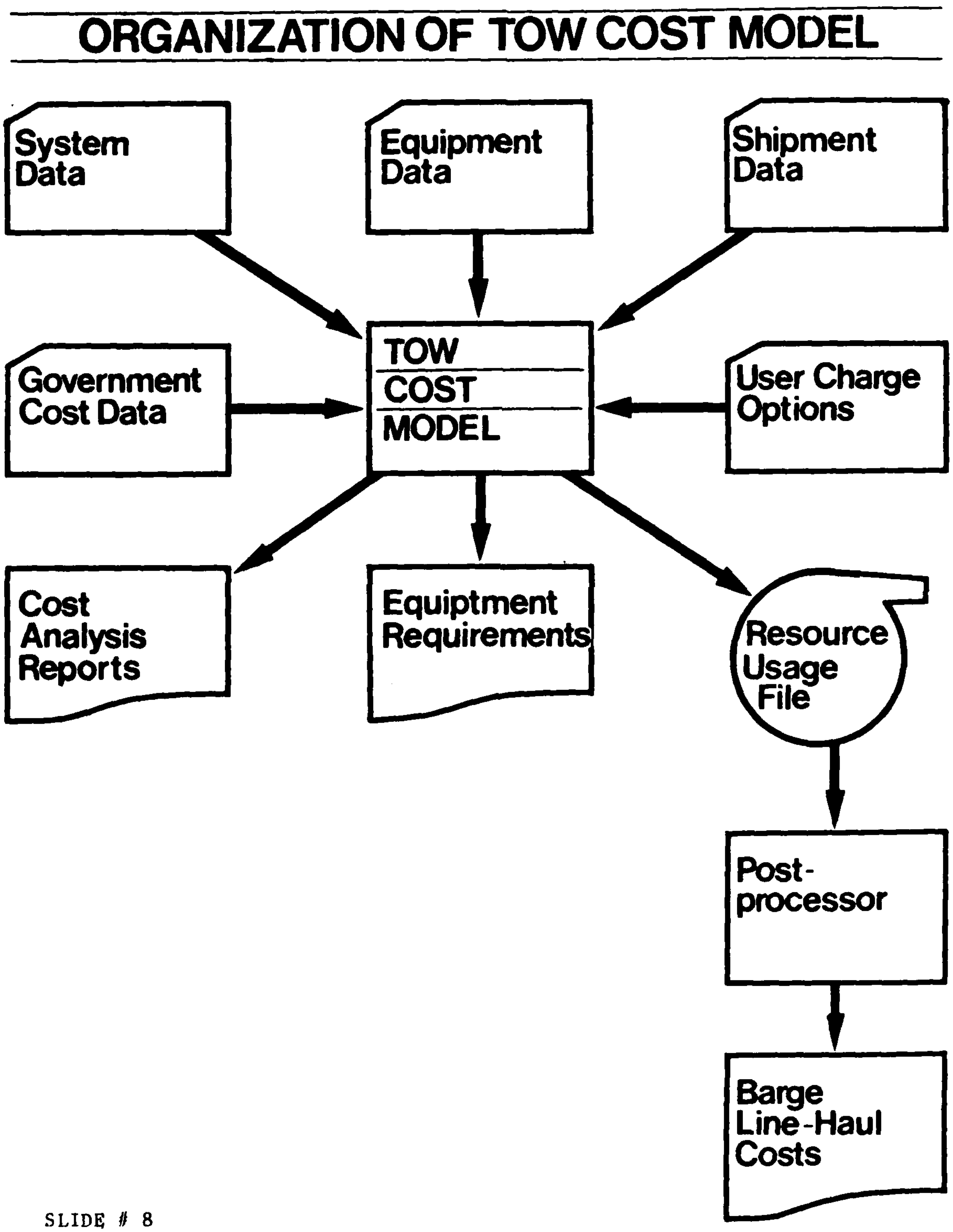


SLIDE # 6

TOW COST MODEL OVERVIEW

- BARGE COSTING MODEL —— NOT SIMULATION MODEL
- MODIFIED AND EXPANDED VERSION OF FLOTILLA MODEL
- COMPUTES BARGE LINE–HAUL COSTS

SLIDE # 7


ORGANIZATION OF TOW COST MODEL
System Data
Equipment Data
Shipment Data
Government Cost Data
TOW COST MODEL
User Charge Options
Cost Analysis Reports
Equiptment Requirements
Resource Usage File
Post-processor
Barge Line-Haul Costs

SLIDE # 8

TOW COST MODEL
PORT–TO–PORT ALGORITHM

- DETERMINES LEAST–COST FLEET FOR EACH MOVEMENT (SUBJECT TO USER SPECIFIED CONSTRAINTS)
- COMPUTES TIME REQUIRED FOR EACH MOVEMENT

  (1) BARGE LOADING & UNLOADING

  (2) AWAIT TOWBOAT

  (3) TOW MAKEUP/BREAKING

  (4) OPEN RIVER TRANSIT

  (5) LOCKAGE

  (6) DELAY

  (7) REFLEETING

- COMPUTES BARGE LINE–HAUL COSTS FOR EACH MOVEMENT BY APPLYING EQUIPMENT OPERATING COSTS PER UNIT OF TIME

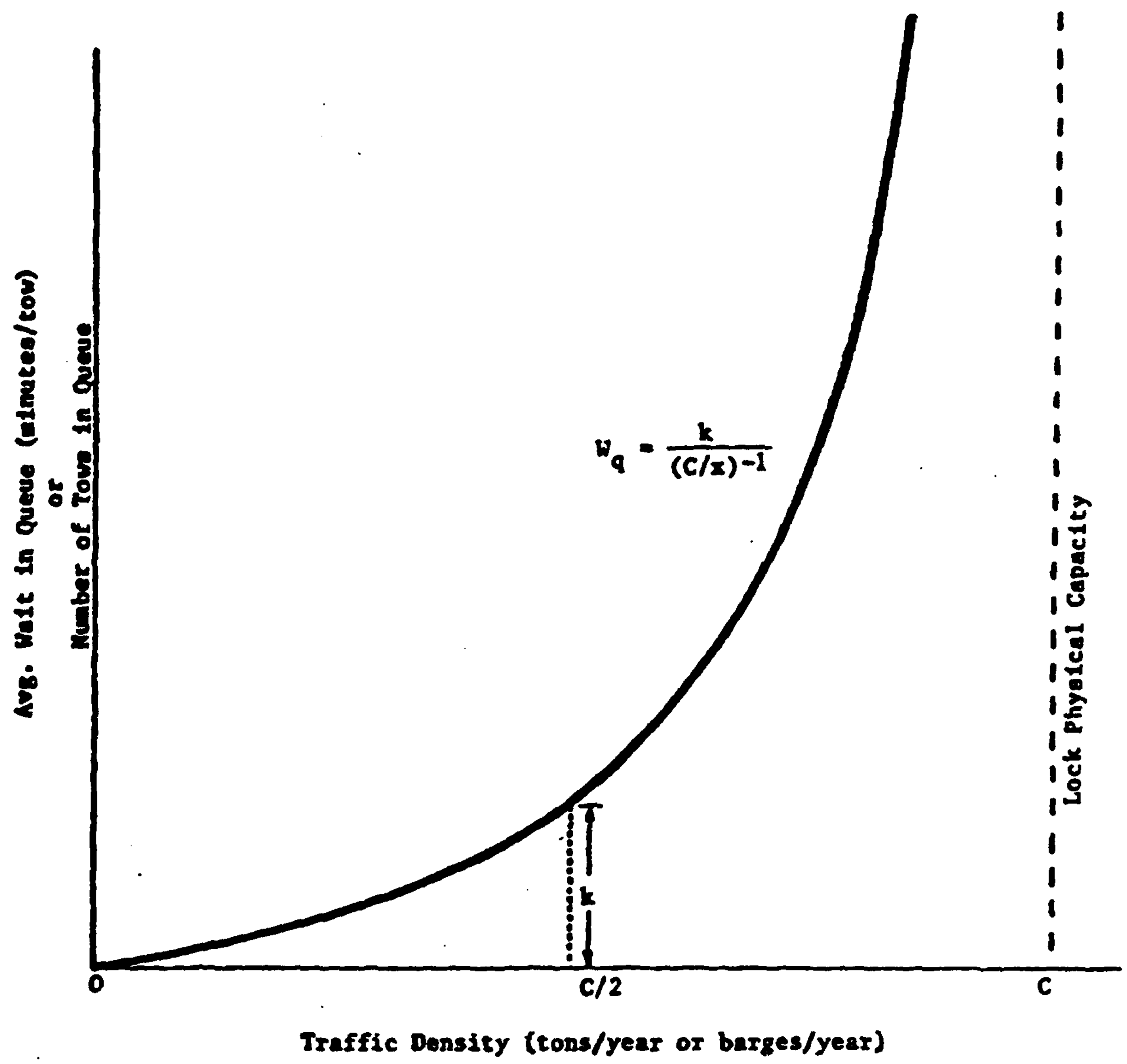
SLIDE # 9

TOW COST MODEL
DATA REQUIREMENTS

(1) WATERWAY PHYSICAL DESCRIPTION

- RIVER SEGMENTS (LENGTH, DEPTH, VELOCITY)
- LOCKS (LOCATION, CAPACITY, LOCKAGE TIME, DELAY FUNCTION)
- PORTS (LOCATION, LOADING, UNLOADING & FLEETING TIMES)
- REFLEETING POINTS (LOCATION & REFLEETING TIMES)

SLIDE # 10



TYPICAL LOCK TRAFFIC-DELAY CURVE

SLIDE #11

TOW COST MODEL
DATA REQUIREMENTS

(2) TOWING EQUIPMENT DESCRIPTIONS

- TOWBOATS (PHYSICAL DIMENSIONS, HORSEPOWER, FUEL CONSUMPTION RATE, FUEL PRICE, OPERATING COSTS)
- BARGES (PHYSICAL DIMENSIONS, CAPACITY, COSTS)

SLIDE #12

TOW COST MODEL
DATA REQUIREMENTS

(3) COMMODITY SHIPMENT LIST

- COMMODITY NAME
- ORIGIN PORT
- DESTINATION PORT
- ANNUAL TONNAGE
- PERCENT DEDICATED EQUIPMENT

SLIDE #13

TOW COST MODEL
DATA REQUIREMENTS

(4) COMMODITY TRANSPORTATION CLASS

- COMMODITY NAMES
- HANDLING CLASS (E.G. DRY BULK, LIQUIDS, SPECIALTY PRODUCTS)
- VALUE/TON
- BARGE TYPE
- INVENTORY HOLDING COSTS FACTOR

SLIDE #14

MODEL OUTPUT

- ANNUAL TOWBOAT UTILIZATION AND COSTS
- ANNUAL BARGE UTILIZATION AND COSTS
- TOW SIZE DISTRIBUTION
- LOCK UTILIZATION
- LOCK COSTS
- PORT UTILIZATION
- PORT COSTS
- SEGMENT COST SUMMARIES
- USER CHARGE SUMMARY
- PORT–TO–PORT COMMODITY MOVEMENTS & COSTS

SLIDE #15

MODEL CALIBRATION

- TOW AND BARGE LOADINGS BY CLASS
- NUMBER LOADED, EMPTY & TOTAL BARGES BY CLASS
- NUMBER OF TOWBOATS BY H.P. SIZE
- TOW SPEEDS BY WATERWAY
- LOCK DELAYS

SLIDE #16

MARGINAL ECONOMIC ANALYSIS MODEL

- USES TOW COST MODEL OUTPUT
- COMPUTES RATIO OF BASE YEAR AND FUTURE YEAR BARGE SHIPPING COSTS (MODELED COSTS)
- ADJUSTS EXISTING BARGE LINE–HAUL RATE FROM MATRIX
- COMPUTES REVISED UNIT RATE SAVINGS FOR EACH MOVEMENT
- RANKS ALL MOVEMENTS FROM HIGHEST–TO–LOWEST UNIT SAVINGS
- PROVIDES CUMULATIVE TOTALS

SLIDE #17

U.S. ARMY CORPS OF ENGINEERS
HUNTINGTON DISTRICT MARGINAL ECONOMIC ANALYSIS

REPORT 1. ANALYSIS OF TOTAL WATERWAY SYSTEM
BASED ON 1976 TRAFFIC LEVELS AND TOWING CONDITIONS
USING TON-MILE AS MEASURE OF OUTPUT AND TOTAL WATERWAY ROUTINGS TO ESTIMATE MARGINAL VARIABLES

						ACCUMULATIVE				RATE SAVINGS IN DOLLARS PER TON MILE		ROUTING FLAG				
RANK	COMM CODE	ORIG PORT	DEST PORT	KTONS IN MOVE	KTON-MILES IN MOVEMENT	KTONS	KTON-MILES	RATE SAVINGS DOLLARS*1000	TRANSPORT COST DOLLARS*1000	AVERAGE	MARGINAL	MON	MON + GAL	MON + WIN	MON + GRN	MON + 52
1936	1	40	49	69	19251	175291	83323320	1113541.12	1649525.30	.0134	.0020	0	0	0	0	0
1937	5	66	87	7	2261	175298	83325581	1113545.46	1649627.36	.0134	.0019	0	0	0	0	0
1938	1	46	96	141	219114	175439	83544695	1113931.80	1651901.69	.0133	.0018	0	0	0	0	0
1939	5	64	74	14	6580	175453	83551275	1113943.84	1652113.93	.0133	.0018	0	0	0	0	0
1940	5	49	58	6	1608	175459	83552883	1113946.66	1652197.81	.0133	.0018	0	0	0	0	0
1941	5	66	82	10	3360	175469	83556243	1113952.56	1652342.71	.0133	.0018	0	0	0	0	0
1942	8	11	49	31	14787	175500	83571030	1113978.29	1653148.71	.0133	.0017	1	1	0	1	0
1943	4	37	44	436	38804	175936	83609834	1114039.33	1657090.15	.0133	.0016	0	0	0	0	0
1944	8	24	93	34	62084	175970	83671918	1114121.95	1658349.51	.0133	.0013	0	0	0	0	0
1945	5	62	74	27	13608	175997	83685526	1114137.88	1658785.83	.0133	.0012	0	0	0	0	0
1946	1	79	77	354	55578	176351	83741104	1114201.60	1661320.47	.0133	.0011	0	0	0	0	0
1947	5	60	90	144	147312	176495	83888416	1114280.80	1663926.87	.0133	.0005	0	0	0	0	0
1948	1	70	96	74	72298	176569	83960714	1114279.32	1664916.99	.0133	-.0000	0	0	0	0	0
1949	5	88	74	87	84477	176656	84045191	1114256.70	1667324.28	.0133	-.0003	0	0	0	0	0
1950	8	24	49	12	5412	176668	84050603	1114254.06	1667637.48	.0133	-.0005	0	0	0	0	0
1951	5	66	90	164	142844	176832	84193447	1114137.62	1670742.00	.0132	-.0008	0	0	0	0	0
1952	5	72	91	3	3135	176835	84196582	1114134.95	1670798.43	.0132	-.0009	0	0	0	0	0
1953	8	85	72	28	16716	176863	84213298	1114115.63	1671575.71	.0132	-.0012	0	0	0	0	0
1954	5	62	91	741	778050	177604	84991348	1112944.85	1686818.08	.0131	-.0015	0	0	0	0	0
1955	1	70	97	390	471900	177994	85463248	1112254.55	1692648.58	.0130	-.0015	0	0	0	0	0
1956	4	54	49	405	35640	178399	85498888	1112189.75	1693867.63	.0130	-.0018	0	0	0	0	0
1957	8	91	72	83	86735	178482	85585623	1112003.00	1696644.81	.0130	-.0022	0	0	0	0	0
1958	5	62	90	207	191889	178689	85777512	1111580.72	1700786.88	.0130	-.0022	0	0	0	0	0
1959	6	90	23	7	11949	178696	85789461	1111552.58	1701051.76	.0130	-.0024	0	0	0	0	0
1960	1	58	96	76	86640	178772	85876101	1111329.90	1702321.72	.0129	-.0026	0	0	0	0	0
1961	8	46	17	13	4589	178785	85880690	1111317.94	1702545.45	.0129	-.0026	0	0	0	0	0
1962	8	90	74	6	6900	178791	85887590	1111291.60	1702785.45	.0129	-.0038	0	0	0	0	0
1963	5	62	94	2	2444	178793	85890034	1111282.00	1702825.63	.0129	-.0039	0	0	0	0	0
1964	1	55	31	17	8245	178810	85898279	1111242.56	1703118.20	.0129	-.0048	0	0	0	0	0
1965	9	58	49	23	6164	178833	85904443	1111207.60	1703552.44	.0129	-.0057	0	0	0	0	0
1966	1	2	4	456	6840	179289	85911283	1111166.56	1706201.80	.0129	-.0060	1	0	0	0	0
1967	1	44	40	306	36108	179595	85947391	1110915.64	1709246.50	.0129	-.0069	0	0	0	0	0
1968	4	16	18	1074	15036	180669	85962427	1110765.28	1712071.12	.0129	-.0100	0	0	0	0	0
1969	8	46	27	5	1280	180674	85963707	1110751.73	1712186.42	.0129	-.0106	0	0	0	0	0
1970	1	2	6	72	2808	180746	85966515	1110720.77	1712527.70	.0129	-.0110	1	0	0	0	0
1971	1	36	38	313	23475	181059	85989990	1110295.09	1714462.04	.0129	-.0181	0	0	0	0	0
1972	1	8	24	73	4088	181132	85994078	1110215.52	1715482.58	.0129	-.0195	1	0	0	0	0
1973	8	33	36	7	315	181139	85994393	1110208.87	1715586.46	.0129	-.0211	0	0	0	0	0
1974	6	71	87	69	16491	181208	86010884	1109613.40	1716840.88	.0129	-.0361	0	0	0	0	0
1975	1	39	40	290	3770	181498	86014654	1109477.10	1717734.08	.0129	-.0362	0	0	0	0	0
1976	8	11	8	4	120	181502	86014774	1109470.30	1717790.84	.0129	-.0567	1	0	0	0	0
1977	1	7	6	336	7392	181838	86022166	1108929.34	1719433.88	.0129	-.0732	1	0	0	0	0
1978	1	18	19	390	3510	182228	86025676	1108402.84	1720529.78	.0129	-.1500	0	0	0	0	0
1979	8	11	24	1	26	182229	86025702	1108398.85	1720546.11	.0129	-.1535	1	0	0	0	0
1980	1	11	21	13	65	182242	86025767	1108385.46	1720620.86	.0129	-.2060	1	0	0	0	0
1981	1	21	11	234	1170	182476	86026937	1108128.06	1721966.36	.0129	-.2200	1	0	0	0	0

??

SLIDE #18

DIVERSION ANALYSIS

- IDENTIFY UNECONOMIC MOVEMENTS
- DELETE "WORST" MOVEMENTS FROM SHIPMENT LIST (SMALL INCREMENTS)
- REPEAT MODELING PROCESS
- REPEAT STEPS 1-3 UNTIL EQUILIBRIUM ACHIEVED (INITIAL)
- TEST FOR OVERDIVERSION OF TRAFFIC
  - SET DELAYS AT EQUILIBRIUM LEVEL
  - RERUN NEGATIVE MOVEMENTS
  - CHECK RESULTS FOR ECONOMIC MOVEMENTS
  - ADD ECONOMIC MOVEMENTS TO INITIAL EQUILIBRIUM SHIPMENT LIST
  - REPEAT MODELING PROCESS
- DEFINE EQUILIBRIUM SOLUTION

SLIDE #19

PROJECT BENEFITS
(MILLION DOLLARS)

SYSTEM SAVINGS

YEAR	WITHOUT PROJECT CONDITION	WITH PROJECT CONDITION	INCREMENTAL PROJECT BENEFITS
1990	$1,500	$1,550	$ 50
2000	1,600	1,700	100
2020	1,700	1,850	150
2040	1,800	2,000	200

SLIDE #20

IMPACT ASSESSMENTS

- TOTAL SYSTEM TRAFFIC
- TRAFFIC AT CRITICAL PROJECTS
- SYSTEM LOCK DELAYS
- DELAYS AT CRITICAL PROJECTS
- TRAFFIC DIVERTED FROM OVERLAND MODES
- OTHER VARIABLES

SLIDE #21

SENSITIVITY EVALUATIONS

- ALTERNATIVE TRAFFIC DEMANDS
- CHANGES IN OVERLAND RATES
- CHANGES IN BARGE RATES
- CHANGES IN FUEL PRICES
- LOCK IMPROVEMENTS ELSEWHERE IN SYSTEM
- USER CHARGE RECOVERY

SLIDE #22

A DISCUSSION AND DESCRIPTION OF THE

GENERAL EQUILIBRIUM MODEL (GEM)*

Two of the initial steps in developing the research plan for assessing the impacts of lock congestion are the development of draft reports and users manuals on the TCM and GEM. The general description of the TCM and MEA in the Systems Evaluation paper is relatively clear, however, the mathematics involved in describing GEM I and GEM II are very difficult to intuitively understand. As a result workshop participants were uncertain about the nature of GEM and the distinction between GEM and MEA. A brief discussion of the GEM model formulation is presented here to provide a basis for assessing the rationale and benefits of attempting to merge the TCM and GEM. Two areas that have caused confusion about GEM. The first area is the mathematics involved in describing GEM. The mathematics (mainly topology) used to describe GEM are clearly specified, however, the notation is extremely difficult to follow. The mathematics in GEM serve two very important purposes: (1) to prove that the model has a solution; and (2) to describe a general navigation system.

The second area of confusion involved the relationship between GEM and the TCM/MEA. The only relationship between GEM and TCM/MEA models is that both models are oriented to maximize system benefits. In this respect MEA is related to GEM. As noted in the GEM I paper, "The GEM approach does not model tow configuration, loading, emptys or backhaul; thus it should be viewed primarily as an alternative to the Marginal Economic Analysis (MEA) procedure developed by Huntington District." GEM and MEA are fundamentally

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*Prepared by James Crew, Browns Associates, Inc.

different algorithms for computing navigation systems benefits. This is a major reason that GEM is difficult to understand; it is difficult to describe the processes that occur in an iterative general equilbrium solution process.

The general problem to be solved in navigation modelling can be summarized as follows:

> For all waterway movements select those which reflect the best utilization of the system (i.e. maximize benefits) given that any individual movement has associated benefits in the form of reduced transportation costs and associated costs in the form of lock delays.

For example, a movement may save $5.00 in transportation rates by using the waterway (with zero lock delays) but given forcasted traffic levels there will be a delay cost of $3.00, resulting in a net benefit of $2.00. Since both the benefits and costs are determined by traffic levels, the general problem is to select that combination of movements yielding the highest total savings minus total costs. The complexity in solving this problem results from the fact that lock delay curves are non-linear. Consequently sophisticated techniques are necessary to arrive at a solution.

The need for GEM or MEA models in solving this problem can be illustrated with an example. Assume a three lock system, with 1,000 prospective waterway movements. Furthermore each of the locks is congested and the optimal solution to the general problem is known to be an amount of delay at each of the three locks equivalent to $.50 per ton. A movement that

traverses all three locks incurs delay costs of $1.50 per ton, a movement traversing only two locks incurs delay costs of $1.00 per ton and any movement traversing only one lock incurs delay costs of $.50 per lock. Knowing the optimal solution for the level of lock delays allows for identification of waterway movements and benefits. All that needs to be done is to examine the transportation rate savings associated with each movement and the number of locks a movement traverses. Three lock movements with savings of at least $1.50 will continue to utilize the waterways, while those with savings less than $1.50 will divert from the waterway to some alternative (cheaper) mode. Two lock movements with savings of at least $1.00 (.50¢ each) will continue to use the waterway. Those movements with savings less than $1.00 (.50¢ each) will divert to some alternative mode. The final step is to sum the savings and tonnages of the movements that will continue to utilize the waterway and subtract the delay costs associated with each movement to obtain net benefits.

When the optimal solution is known - assume that 900 of the hypothetical 1,000 movements are forecasted to use the waterway given the future levels of lock delay. However, the optimal solution is <u>not</u> known before hand and must be computed. In the TCM/MEA formulation an initial solution will be found based on 1,000 movements. Lock delay levels will then be estimated based on all 1,000 movements. Since the optimal configuration only allows for 900 movements the initial 1,000 movement solution will yield movements that have negative rate savings. These movements do not benefit from the waterway and will divert to an alternative cheaper mode. Using the MEA, an analyst would examine all 1,000

movements and estimate which movements should be eliminated from the system. The TCM/MEA algorithm would be reiterated until the 900 movements that, by assumption, are embodied in the optimal solution are obtained. Benefits will then be estimated.

What GEM contributes to this analysis is that it formalizes the intuitive search process undertaken by the MEA approach. GEM utilizes a pricing convention that accurately describes the marginal contribution of each movement to system benefits, by ensuring that each solution of the iterative process is feasible. GEM finds those combinations of prospective movements that satisfy the constraints (locks) of the general problem and then searches through these alternative feasible solutions to obtain the optimal solution that <u>maximizes</u> benefits.

The contribution of GEM can be illustrated using the above example. Assume it is known that the optimal solution has exactly 900 movements that continue to use the waterway, but the levels of lock delays associated with the solution are unknown. One method of finding the levels of lock delays for the optimal solution would be to compute the benefits and delays associated with all possible combinations of 900 movements from the original 1,000 prospective movements. This is a conceptually feasible approach. However, there are approximately 8 trillion possible combinations that would have to be searched. The analyst searching these combinations would have to know a great deal about the system to eliminate a large portion of the possible combinations. However, even if the analyst could eliminate 99.9 percent of the possible combinations, this would still leave about

8 million combinations to be searched. During the application of a navigation model, the analyst does not know the number of movements in the optimal solutions. Nothwithstanding the ability to eliminate 99.9% of the possible solutions based on intuitive knowledge of the system the analyst would still be faced with trillions or quadrillions of potential solutions that need to be examined!

At this point in the solution process the contribution of GEM becomes significant. The ability of GEM to find the optimal solution is the reason that it is superior to the intuitive solution procedure of MEA. It is important to note that the advantage of GEM is not derived from the general equilibrium problem but by the requirement that any iterative solution be feasible; the use of solution techniques, such as MINOS and its non-linear applications, to reduce the number of prospective solutions to be examined and provide a correct systems cost associated with each of the prospective solutions; and application of linear algebra that greatly reduces the prospective number of solutions that need to be searched.

It is this last aspect of GEM and MINOS that provides the superiority of GEM over MEA. The first two attributes of GEM and MINOS noted above effectively formalize in a two-step process the analyst's knowledge embodied in the MEA procedure. In essence the two steps utilize the analyst's knowledge twice to reduce the number of solutions by 99.9% and then again by 99.9%. However, given the large number of prospective solutions to the general problem, it would still not be feasible to search through all possible solutions. (In the above example, this would still leave 890,000

solutions initially!). In order to enable the analyst to derive a solution exhaustive knowledge of the system is required because the number of prospective solutions is so large.

GEM and MINOS reduce number of solutions drastically by applying linear algebra. Mathematically, the technique is that the basis of the space within which the general problem is solved has dimensionality equal to the number of locks that describe the system. This technique allows the computer to do something the analyst cannot perform by describing the problem in a different but equivalent manner. The MEA views the lock system by describing it in terms of system movements. The movements are always greater than the number of locks which leads to an incredibly large number of potential solutions. The MINOS/GEM formulation describes the movements by the number of locks in the system. This procedure drastically reduces the number of solutions which are initially considered so that the type of search procedure embodied in MEA becomes feasible.

The GEM/MINOS solution algorithm can be described as a three step procedure; First, given the formulation of the general evaluation problem, MINOS identifies the most important elements. These elements are the locks that comprise the system. Second, using the feasibility constraints imposed by GEM the process determines which lock constraints are the most important elements of the problem. Each lock has a marginal movement associated with it that may be in the optimal solution. Third, using a pricing convention (which corresponds to shadow pricing in linear programming) MINOS the determines if the optimal solution has been found.

If not, the pricing convention is used to select another potential solution until the optimal solution is obtained. In this respect the pricing convention of GEM/MINOS corresponds to the search process of MEA.

GEM computes system benefits and system delays. An important added feature of MINOS is that it determines not only the actual solution but it also determines the Lagrangians associated with each constraint in the system. Thus MINOS provides not only an optimal solution to the general problem, but also indicates future avenues of investigation within the framework of the general problem.

The nature of the GEM/MINOS solution and the possibility of merging the TCM with GEM/MINOS (and its non-linear formulation) indicate future areas of research. The MEA solution formulation represents a non-linear solution algorithm based on successive linear approximations to the actual solution. This type of solution algorithm can be used to approximate the optimal solution. However, non-linearity that can accurately be accommodated by this technique is limited. The solution technique embodied in GEM/MINOS allows for the incorporation of at least two important types of problems that characterize navigation modeling: (1) theoretical underpinnings of most transportation economic analysis involves considerable non-linearities; and (2) important problems in transportation modelling. For example the impact of transit time variability on logistics costs, require the solution of line integrals or the incorporation of unsupported assumptions. The GEM/MINOS formulations allows for a wide variety of functional forms to represent non-linear transportation cost functions.

If the GEM/Minos solution technique can be merged with the TCM (or other types of costing and transportation models) it will allow for a broader investigation of navigation and transportation impacts within a systems framework. Concurrently GEM represents a system analysis which the Corps can use to fulfil its mission of maintenance and development of the inland waterways system.

A SYSTEM EQUILIBRIUM MODEL FOR ECONOMIC POLICY ANALYSIS OF NATIONAL INLAND WATERWAYS NAVIGATION

GEM 1

by

Don Sweeney
U.S. Army Corps of Engineers
St. Louis District
St. Louis, Missouri

for

Navigation Division
Institute for Water Resources
U.S. Army Corps of Engineers
Ft. Belvoir, Virginia

December, 1983

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Appendixes

A. Flow Diagram

B. Fortran IV Source Listing

C. Sample Job Control Language

D. Sample Input Data

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F. Mathematical Description and Proof of Existance of Systemic Equilibrium

G. Test Case

Introduction and Description of General Equilibrium Model (GEM)

I. Introduction

Economic benefits of navigation projects consist of two components, transportation savings and lock delay reductions resulting from navigation improvements. When demand for lock usage exceeds the available supply of the lock, some traffic (barge movements carrying commodities of coal, chemicals, petroleum products, wheat, corn, etc.) cannot utilize the lock. In particular, as the amount of traffic passing through a lock increases, delays at the lock increase due to increased levels of congestion. This raises the cost of transportation on the waterway. At some point the increased costs will exceed those of some alternative mode (e.g., railroad, trucking) for some movements, and shippers of these movements will find it more economical to use an alternative transportation mode.

II. Model Description

1. GEM Capability

GEM is a dynamic "economic capacity" model of a system of locks rather than a "physical capacity" model. GEM simultaneously addresses the lock congestion, commodity shipments (tonnage, delay and rate differentials between modes for a system of locks, given (1) potential movements and

gross rate savings for each movement and (2) capacity parameters for each lock. (In a physical capacity model, the rate differential is often treated outside of the model.) Namely, for each lock, GEM establishes an equilibrium point where the gross rate savings on the waterway equals the delay costs on the waterway. The equilibrium point indicates the point where the shipper is indifferent among various modes. The equilibrium point at each individual lock, however, is dependent on the equilibrium point at every other lock included in the system; therefore, the system of locks has to be simultaneously evaluated so that various equilibrium points can be arrived at simultaneously. The GEM approach does not model tow configuration, loading, emptys or backhauls; thus it should be viewed primarily as an alternative to the Marginal Economic Analysis (MEA) procedure developed by Huntington District.

The outputs of this simultaneous modeling of locks at equilibrium in the system are (1) the maximum delay which can be tolerated, (2) the percentage of traffic which would be diverted from the waterway system, (3) the tonnage which can be expected to pass through each lock, and (4) the navigation benefits of lock improvement.

Obviously, the rates could be adjusted to reflect proposed user charges, the delay-capacity curves could be adjusted to reflect proposed system improvements, and so forth. Thus flexibility allows examination of system responses to various situations, physical or economic.

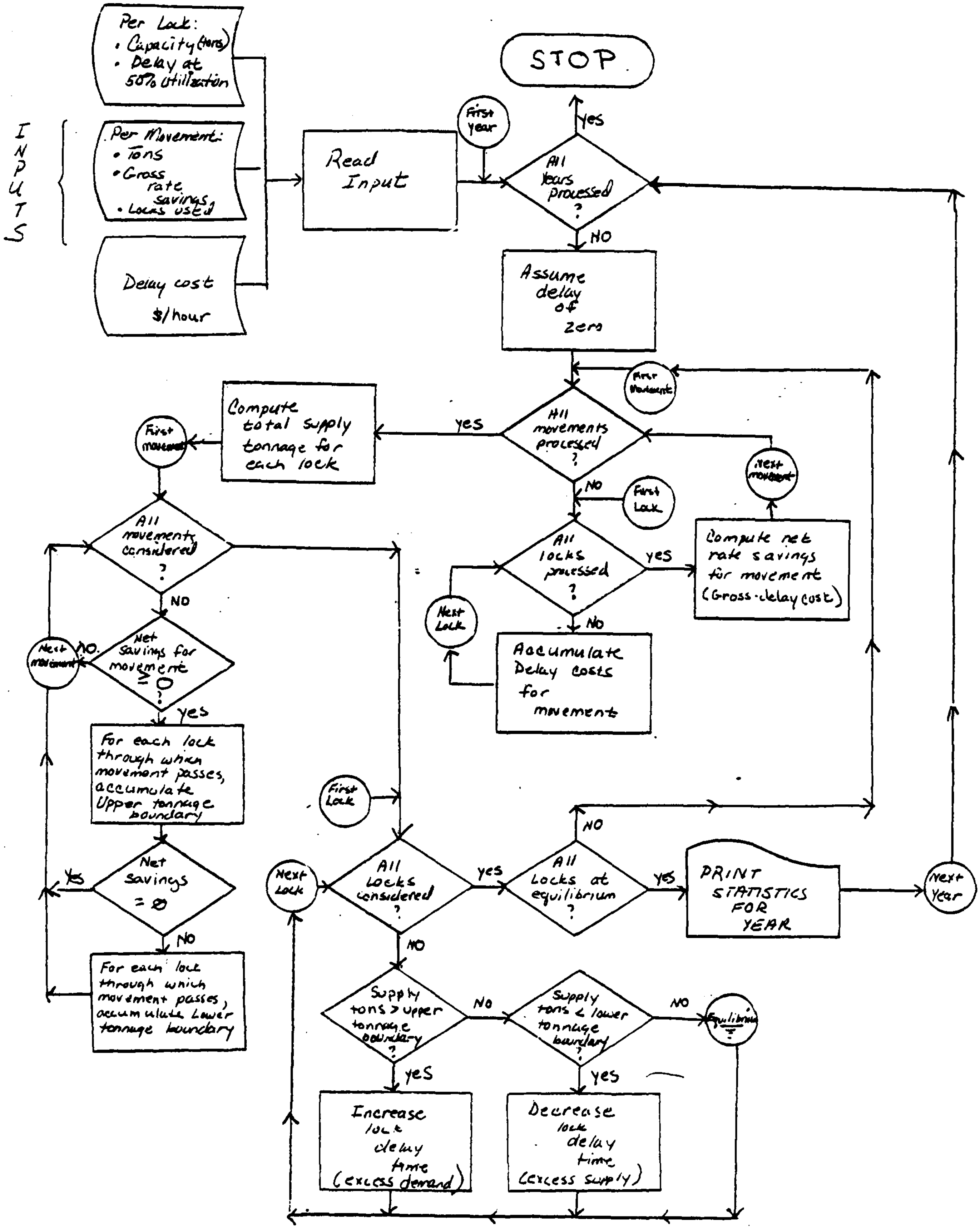
Appendixes A and B contain a flow diagram and a listing of a Fortran IV computer program which implements the algorithm. Appendix C is job

control language which can be used to access the data and execute the program. Appendixes D and E are sample input and output for the test case described in Appendix G. Appendix F is a discussion of the mathematics involved and a proof that the systemic equilibrium exists.

APPENDIX A

GENERAL EQUILIBRIUM MODEL

FLOW DIAGRAM


Per Lock:
• Capacity (tons)
• Delay at 50% utilization
INPUTS
Per Movement:
• Tons
• Gross rate savings
• Locks used
Delay cost $/hour
Read Input
STOP
First year
All years processed ?
yes
NO
Assume delay of zero
First movement
All movements processed ?
yes
NO
Compute total supply tonnage for each lock
First movement
First Lock
All locks processed ?
yes
NO
Compute net rate savings for movement (Gross - delay cost)
Next movement
Next Lock
Accumulate Delay costs for movement
All movements considered ?
NO
Next movement
Net savings for movement ≥ 0 ?
yes
For each lock through which movement passes, accumulate Upper tonnage boundary
Net savings = 0
yes
NO
For each lock through which movement passes, accumulate Lower tonnage boundary
First Lock
Next Lock
All locks considered ?
yes
NO
All Locks at equilibrium ?
yes
NO
PRINT STATISTICS FOR YEAR
Next Year
Supply tons > upper tonnage boundary ?
NO
yes
Supply tons < lower tonnage boundary ?
NO
yes
Equilibrium
Increase lock delay time (excess demand)
Decrease lock delay time (excess supply)

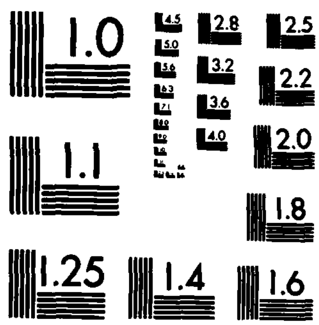
APPENDIX B

FORTRAN IV SOURCE LISTING

```
      DO 12 L=1,LOCKS
      X(L)=1
   12 CONTINUE
      DO 14 L=1,LOCKS
      IF(TS(L).GT.(TDU(L)+.5))GO TO 13
      IF(TS(L).LT.(TDB(L)-.5))GO TO 14
      X(L)=0
      GO TO 14
   13 X(L)=-1
   14 CONTINUE
      DO 15 L=1,LOCKS
      IF(X(L).NE.0)GO TO 16
   15 CONTINUE
      GO TO 33
   16 L=1
      DO 28 L=1,LOCKS
      IF(X(L).EQ.-1)GO TO 17
      IF(X(L).EQ.1)GO TO 23
      INC(L)=0.
      GO TO 28
   17 INC(L)=-10000.
      DO 18 I=1,NMOVE
      IF(NH(I).GE.-.00001)GO TO 18
      IF(LI(I,L).EQ.0)GO TO 18
      DEN=0.
      DO 20 J=1,LOCKS
      IF(X(J).GE.0)GO TO 20
      DEN=DEN+FLOAT(LI(I,J))
   20 CONTINUE
      IF((NH(I)/DEN).LT.INC(L))GO TO 18
      Z(L)=I
      INC(L)=NH(I)/DEN
   18 CONTINUE
      IF((D(L)+(INC(L)/.0356)).GT..00001)GO TO 19
      INC(L)=(K(L)*(TDB(L)/CAP(L))/(1.-(TDB(L)/CAP(L))))-D(L)
      GO TO 28
   19 INC(L)=INC(L)/.0356
      GO TO 28
   23 INC(L)=10000.
      DO 24 I=1,NMOVE
      IF(NH(I).LE..00001)GO TO 24
      IF (LI(I,L).EQ.0)GO TO 24
      DEN=0.
      DO 26 J=1,LOCKS
      IF(X(J).LE.0)GO TO 26
      DEN=DEN+FLOAT(LI(I,J))
   26 CONTINUE
      IF((NH(I)/DEN).GT.INC(L))GO TO 24
      Z(L)=I
      INC(L)=NH(I)/DEN
   24 CONTINUE
      IF(INC(L).NE.10000.)GO TO 25
      PRINT 80,L
      GO TO 200
   80 FORMAT (I5)
```

AD-A153 383 PROCEEDINGS FROM A WORKSHOP ON ECONOMIC ANALYSIS OF INLAND NAVIGATION AND..(U) ARMY ENGINEER INST FOR WATER RESOURCES FORT BELVOIR VA FEB 85 IWR-85-PR-1 2/3

UNCLASSIFIED F/G 13/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

```
 25 INC(L)=INC(L)/.0356
 28 CONTINUE
    DO 501 L=1,LOCKS
    IF(X(L).GT.0)GO TO 530
501 CONTINUE
    DO 503 L=1,LOCKS
    IF(X(L).EQ.0)GO TO 503
    INC(L)=(K(L)*(TDU(L)/CAP(L))/(1.-(TDU(L)/CAP(L))))-D(L)
503 CONTINUE
530 DO 29 L=1,LOCKS
    IF(INC(L).NE.0.)GO TO 30
 29 CONTINUE
    GO TO 33
 30 DO 31 J=1,LOCKS
    D(J)=D(J)+INC(J)
 31 CONTINUE
    DO 201 L=1,LOCKS
    IF((ABS(INC(L)+INC1(L))).GE..00001)GO TO 202
201 CONTINUE
    DO 203 L=1,LOCKS
    IF(X(L).NE.-1)GO TO 204
    TS(L)=TDU(L)
    GO TO 203
204 IF(X(L).EQ.0)GO TO 203
    TS(L)=TDB(L)
203 CONTINUE
    GO TO 33
202 ITER=ITER+1
    GO TO 4
 33 DO 32 L=1,LOCKS
    IF(X(L).EQ.0)GO TO 32
    D(L)=K(L)*(TS(L)/CAP(L))/(1.-(TS(L)/CAP(L)))
 32 CONTINUE
 34 PRINT 305
305 FORMAT (1H )
    PRINT 83,YEAR,ITER
    PRINT 300
300 FORMAT (1H )
    PRINT 301
301 FORMAT (3X,5HEQUIL,8X,6HSUPPLY,6X,4HLAST,5X,7HMINIMUM,5X,
   N7HMAXIMUM)
    PRINT 302
302 FORMAT (3X,5HDELAY,1X,4HLOCK,2X,8H TONNAGE,5X,4HINCR,5X,
   N7HTONNAGE,5X,7HTONNAGE)
    DO 36 L=1,LOCKS
    PRINT 82,D(L),L,TS(L),INC(L),TDB(L),TDU(L)
 82 FORMAT (F8.4,2X,I2,F11.0,X,F8.4,X,F11.0,X,F11.0)
 36 CONTINUE
    DO 141 I=1,NMOVE
    DELCOST=0.
    DO 142 L=1,LOCKS
    DELCOST=DELCOST+FLOAT(LI(I,L))*D(L)*.0356
142 CONTINUE
    NH(I)=GH(I)-DELCOST
141 CONTINUE
```

```
 83 FORMAT (1X,4HYEAR,I3,4X,10HITERATIONS,1X,I4)
    TOTBEN=0.
    DO 107 I=1,NMOVE
    IF(NH(I).GT.0.00001)GO TO 106
    NH(I)=0.
106 TOTBEN=TOTBEN+TONS(I,YEAR)*NH(I)
107 CONTINUE
    PRINT 108,TOTBEN
108 FORMAT (7H ******,17H TOTAL BENEFITS= ,F10.2,7H ******)
100 CONTINUE
200 END
```

APPENDIX C

SAMPLE JOB CONTROL LANGUAGE

The following job control language can be used to execute the program on a Control Data Cyber series computer running the Network Operating System (NOS) (e.g. that used by Control Data Corporation who are currently contracted to provide Corps teleprocessing services).

Assume the data has been prepared in the format presented in Appendix D. The data and programs are permanent disk files named DATA and PROG, respectively. "USERN", "PASSWORD", "CHARGES" and "PROJECT" should be replaced with the appropriate codes. All statements begin in character position one:

```
/JOB
JOB,CM100000,P1.
USER,USERN,PASSWORD,KOE.
CHARGE,CHARGEN,PROJECT.
GET,TAPE5=DATA.
GET,PROG.
FTN,I=PROG.
LGO.
```

APPENDIX D

SAMPLE INPUT DATA

This portion of the input file shows system operating characteristics. the first data line shows the number of potential movements, the number of constraint points, and the number of years in the analysis. The remaining lines are parameters for the tonnage-delay relationships at the sixteen system constraint points.

```
212  16  7
0.725 53500.
0.725 53500.
0.725 53500.
0.725 53500.
0.725 53500.
0.725 53500.
0.725 53500.
0.725 53500.
0.725 53500.
0.725 53500.
0.725 53500.
0.725 53500.
1.683 23000.
0.725 53500.
0.725 53500.
0.725 53500.
```

DELAY FUNCTION PARAMETERS
THE FIRST IS DELAY AT 50% UTILIZATION. THE SECOND IS ABSOLUTE PHYSICAL CAPACITY OF CONSTRAINT POINT. THE TONNAGE DELAY RELATIONSHIP CURRENTLY USED IS

$$D(L) = K(L)\left(\frac{TONS}{CAP(L)}\right)\left(1-\frac{TONS}{CAP(L)}\right)^{-1}.$$

ANY NON-DECREASING FUNCTION MAY BE USED HOWEVER.

Below is the portion of the input file relating to potential movements desirous of transiting the above system. The first seven columns show the total tonnage of that movement in the years of analysis. Then there is a 16 column lock usage indicator vector with a 1 in any given column indicating that movement uses that lock if it transits the system. The final data column shows the gross rate savings of each movement with no delays at system constraint points.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	INDICATOR VECTOR	G.R.S.
43.	50.	67.	89.	110.	131.	143.	000011	4.20
10.	12.	16.	20.	25.	30.	33.	000011	.77
22.	25.	34.	45.	56.	67.	73.	111111	.59
4759.	5489.	7395.	9711.	12027.	14343.	15715.	111111	1.2[illegible]
4.	5.	6.	8.	10.	12.	13.	111111	[illegible]
124.	143.	192.	252.	312.	372.	408.	111111	3.44
8.	9.	12.	16.	20.	24.	26.	111111	1.[illegible]
8.	9.	13.	17.	21.	25.	27.	111111	[illegible]
7.	8.	10.	14.	17.	20.	22.	111111	3.[illegible]
59.	68.	91.	120.	149.	177.	194.	111111	2.[illegible]
7.	8.	11.	15.	18.	21.	23.	111111	[illegible]
39.	45.	61.	80.	99.	118.	128.	111111	1.[illegible]
10.	11.	15.	20.	24.	29.	32.	111111	2.[illegible]
86.	99.	133.	175.	216.	258.	283.	111111	6.[illegible]
33.	38.	51.	68.	84.	100.	109.	111111	2.[illegible]
56.	65.	87.	114.	142.	169.	185.	111111	2.[illegible]
10.	12.	16.	21.	26.	31.	33.	111111	3.[illegible]
40.	46.	62.	81.	100.	119.	131.	111111	6.[illegible]
2.	2.	3.	4.	5.	6.	6.	111111	6.05

PROJECT	Page 2 of 4	COMPUTED BY	DATE
SUBJECT		CHECKED BY	DATE

136.	163.	221.	291.	361.	432.	460.	111111	6.[illegible]
15.	18.	25.	33.	41.	49.	52.	111111	7.[illegible]
7.	8.	11.	14.	18.	21.	22.	111111	7.[illegible]
39.	47.	63.	83.	103.	124.	132.	011111	3.54
37.	45.	60.	80.	99.	118.	126.	011111	2.[illegible]
1100.	1315.	1781.	2349.	2917.	3485.	3712.	011110	3.[illegible]
7.	9.	12.	16.	20.	23.	25.	011110	3.91
118.	141.	191.	252.	313.	374.	398.	001111	3.[illegible]
3.	3.	4.	6.	7.	8.	9.	111111	3.[illegible]
94.	109.	147.	193.	238.	284.	312.	111111	1.[illegible]
45.	51.	69.	91.	113.	134.	147.	111111	3.[illegible]
306.	354.	474.	639.	805.	970.	1037.	111111	4.[illegible]
20.	23.	30.	41.	51.	62.	66.	111111	4.[illegible]
473.	547.	732.	988.	1244.	1499.	1602.	111111	4.[illegible]
1420.	1642.	2198.	2966.	3733.	4501.	4808.	111111	2.[illegible]
494.	571.	765.	1032.	1299.	1566.	1673.	111111	4.[illegible]
374.	432.	578.	780.	982.	1184.	1264.	111111	5.[illegible]
224.	259.	347.	468.	589.	710.	759.	111111	4.[illegible]
116.	134.	179.	242.	304.	367.	392.	111111	3.[illegible]
1371.	1585.	2122.	2863.	3604.	4345.	4642.	111110	4.[illegible]
155.	179.	240.	323.	407.	491.	524.	111110	5.1[illegible]
1140.	1318.	1765.	2381.	2997.	3613.	3860.	111100	2.9[illegible]
4.	5.	6.	9.	11.	13.	14.	111100	2.1[illegible]
11.	13.	18.	24.	30.	36.	39.	111100	3.9[illegible]
27.	32.	42.	57.	72.	87.	92.	011111	4.9[illegible]
203.	235.	315.	425.	534.	644.	688.	011111	5.4[illegible]
83.	96.	129.	173.	218.	263.	281.	011111	4.7[illegible]
105.	122.	163.	219.	276.	333.	356.	011111	4.3[illegible]
96.	108.	140.	169.	198.	227.	238.	000011	4.2[illegible]
2.	3.	3.	4.	5.	5.	6.	000011	6.1[illegible]
9.	11.	14.	17.	19.	22.	23.	011111	3.4[illegible]
15.	17.	22.	27.	31.	36.	38.	111111	1.2[illegible]
6.	7.	9.	11.	13.	15.	16.	111111	4.2[illegible]
8.	9.	12.	15.	17.	20.	21.	011111	.40
5.	6.	8.	10.	11.	13.	13.	111000	4.1[illegible]
257.	290.	378.	455.	532.	609.	640.	011100	1.3[illegible]
13.	15.	21.	28.	35.	42.	44.	111111	7.11
6.	7.	9.	12.	15.	18.	19.	111111	9.91
14.	16.	22.	29.	37.	44.	47.	111111	5.56
3.	3.	4.	6.	7.	9.	10.	111111	8.37
19.	22.	29.	39.	48.	58.	62.	111111	5.56
6.	7.	10.	13.	17.	20.	21.	111111	7.40
24.	28.	37.	50.	62.	75.	80.	111111	7.40
2.	3.	4.	5.	6.	8.	8.	111111	7.97
6.	6.	9.	12.	15.	17.	19.	111111	10.08
5.	6.	8.	11.	14.	17.	18.	111111	10.08
49.	57.	76.	102.	128.	153.	164.	111111	9.5[illegible]
12.	14.	18.	25.	31.	37.	40.	111111	7.1[illegible]
103.	120.	160.	215.	269.	324.	345.	111111	11.9[illegible]
19.	22.	29.	39.	49.	59.	63.	111111	11.6[illegible]
78.	90.	121.	162.	208.	244.	261.	111111	4.2[illegible]
2.	3.	4.	5.	6.	7.	8.	111111	6.0[illegible]
7.	8.	10.	14.	17.	21.	22.	000001	3.5[illegible]
5.	5.	7.	10.	12.	15.	16.	000001	3.5[illegible]
13.	15.	21.	28.	35.	42.	44.	000001	5.9[illegible]
2.	2.	3.	4.	5.	7.	7.	000001	4.[illegible]
30.	35.	47.	63.	79.	95.	102.	000001	5.[illegible]
9.	11.	14.	19.	24.	28.	30.	000001	5.[illegible]
2.	3.	4.	5.	6.	7.	8.	011111	7.[illegible]
10.	11.	15.	20.	25.	30.	32.	011111	[illegible]

PROJECT		COMPUTED BY	DATE
SUBJECT		CHECKED BY	DATE

4.	5.	7.	9.	11.	13.	14.		000011	2.[illegible]
162.	194.	277.	377.	466.	577.	646.		000001	5.[illegible]
25.	30.	43.	58.	72.	89.	100.		000001	[illegible]
56.	67.	96.	131.	162.	200.	224.		000001	[illegible]
5.	6.	8.	8.	13.	17.	19.		011111	7.[illegible]
39.	47.	67.	91.	113.	140.	156.		111111	4.[illegible]
363.	435.	619.	844.	1043.	1293.	1446.		111111	4.[illegible]
16.	19.	27.	36.	45.	55.	62.		111111	2.[illegible]
291.	367.	557.	823.	1088.	1354.	1784.		001111	8.29
7.	9.	13.	19.	25.	32.	42.		001111	6.20
63.	80.	121.	179.	237.	295.	389.		001111	2.20
64.	81.	124.	182.	241.	300.	396.		001111	6.75
16.	20.	31.	46.	61.	75.	99.		001111	7.79
15.	19.	28.	42.	56.	69.	91.		001111	6.[illegible]4
35.	44.	66.	98.	129.	161.	212.		001111	8.[illegible]8
29.	37.	55.	82.	108.	135.	178.		001111	11.65
8.	10.	16.	23.	31.	39.	51.		111111	8.[illegible]0
13.	16.	24.	36.	47.	59.	77.		111111	9.[illegible]
8.	10.	15.	22.	30.	37.	48.		000011	3.[illegible]
23.	30.	45.	66.	88.	109.	144.		000011	9.[illegible]
27.	34.	51.	76.	100.	124.	164.		000011	6.[illegible]5
5.	6.	7.	9.	11.	13.	21.		111111	2.50
4.	5.	7.	9.	11.	14.	16.		000011	6.[illegible]
22.	25.	34.	44.	58.	74.	81.	1111111111	11	[illegible]
1182.	1354.	1842.	2391.	3091.	3891.	4232.	1111111111	11	1.[illegible]
556.	598.	1.	1.	1.	1.	1.	1111111111	11	2.[illegible]
1423.	1657.	2345.	3193.	4182.	5358.	5867.	1111111111	11	.57
161.	179.	234.	295.	370.	451.	486.	1111111111	11	2.22
20.	25.	39.	57.	81.	114.	129.	1111111111	11	2.49
194.	224.	316.	422.	563.	723.	792.	1111111111	11	3.[illegible]1
1825.	2124.	3007.	4093.	5362.	6870.	7523.	1111111111	11	.80
31.	36.	49.	65.	86.	113.	125.	1111111111	11	1.[illegible]
15.	17.	22.	28.	35.	43.	47.	1111111111	11	1.[illegible]
148.	172.	244.	332.	435.	556.	609.	1111111111	11	1.[illegible]
56.	58.	65.	74.	84.	96.	101.	1111111111	11	5.[illegible]
32.	33.	37.	43.	48.	55.	58.	1111111111	11	1.22
34.	38.	51.	66.	84.	108.	118.	1111111111	11	.44
11.	12.	14.	16.	18.	21.	22.	1111111111	11	2.[illegible]6
63.	66.	74.	87.	100.	115.	121.	1111111111	11	1.[illegible]2
23.	24.	27.	32.	36.	42.	44.	1111111111	11	1.02
14.	15.	17.	19.	22.	26.	27.	1111111111	11	.81
271.	306.	411.	543.	716.	943.	1043.	1111111111	11	2.47
30.	34.	45.	60.	79.	104.	115.	1111111111	11	.53
10.	11.	14.	18.	22.	28.	30.	1111111111	11	1.37
44.	45.	51.	57.	64.	72.	76.	1111111111	11	.89
92.	108.	158.	217.	298.	402.	447.	1111111111	11	3.[illegible]
92.	108.	158.	217.	298.	402.	447.	1111111111	11	4.04
25.	25.	26.	28.	31.	34.	35.	1111111111	11	1.55
25.	25.	26.	28.	31.	34.	35.	1111111111	11	1.45
19.	21.	29.	37.	47.	61.	66.	1111111111	11	1.21
11.	12.	15.	18.	22.	25.	26.	1111111111	11	3.17
272.	311.	427.	555.	718.	895.	970.	1111111111	11	.43
21.	23.	29.	34.	41.	48.	51.	1111111111	11	.32
20.	21.	25.	30.	35.	40.	43.	1111111111	11	.32
75.	84.	108.	133.	162.	192.	205.	1111111111	11	[illegible]
75.	84.	108.	133.	162.	192.	205.	1111111111	11	[illegible]
19.	20.	23.	27.	31.	35.	37.	1111111111	11	[illegible]
24.	27.	36.	47.	63.	81.	89.	1111111111	11	[illegible]
16.	17.	19.	21.	24.	26.	27.	1111111111	11	[illegible]
1760.	2016.	2740.	3562.	4606.	5802.	6314.	1111111111	11	[illegible]
216.	242.	988.	1000.	1000.	1000.	1000.	1111111111	11	[illegible]
107.	112.	126.	140.	154.	171.	177.	1111111111	11	[illegible]
83.	102.	164.	244.	362.	512.	579.	1111111111	11	[illegible]

PROJECT						Page 4 of 4	COMPUTED BY		DATE
259.	311.	466.	649.	898.	1210.	1346.	1111111111	11	.[illegible]
49.	60.	90.	125.	172.	232.	259.	1111111111	11	.70
49.	58.	86.	119.	163.	216.	239.	1111111111	11	.82
135.	160.	237.	327.	448.	614.	689.	1111111111	11	.4[illegible]
112.	115.	126.	141.	157.	173.	180.	1111111111	11	1.[illegible]
97.	108.	140.	179.	227.	282.	306.	1111111111	11	.[illegible]
74.	83.	111.	143.	183.	228.	247.	1111111111	11	1.[illegible]
44.	48.	61.	78.	99.	126.	137.	1111111111	11	.[illegible]
45.	50.	65.	84.	107.	134.	145.	1111111111	11	.5[illegible]
71.	80.	111.	147.	193.	248.	271.	1111111111	11	.[illegible]
97.	108.	142.	182.	232.	290.	315.	1111111111	11	.56
33.	38.	54.	72.	95.	122.	134.	1111111111	11	.63
97.	108.	142.	182.	232.	290.	315.	1111111111	11	.69
37.	41.	56.	73.	97.	125.	137.	1111111111	11	.76
1408.	1626.	2276.	3097.	4202.	5600.	6215.	1111111111	11	.56
1524.	1846.	2825.	4011.	5658.	7636.	8499.	1111111111	11	.56
13.	15.	19.	23.	29.	36.	39.	1111111111	11	.73
22.	24.	28.	33.	38.	45.	47.	1111111111	11	1.20
194.	221.	307.	390.	505.	630.	683.	1111111111	11	.70
194.	221.	307.	390.	505.	630.	683.	1111111111	11	.57
3552.	4134.	5851.	7966.	10434.	13367.	14638.	1111111111	11	1.[illegible]
353.	404.	546.	701.	898.	1129.	1228.	1111111111	11	1.[illegible]
34.	38.	49.	63.	80.	99.	107.	1111111111	11	1.20
64.	66.	74.	84.	94.	106.	111.	1111111111	11	1.35
13.	15.	20.	25.	33.	40.	43.	1111111111	11	.40
13.	15.	20.	25.	30.	37.	40.	1111111111	11	.4[illegible]
19.	24.	39.	58.	85.	121.	136.	1111111111	11	.4[illegible]
8.	9.	10.	11.	12.	13.	13.	1111111111	11	.4[illegible]
14.	16.	21.	28.	36.	48.	53.	1111111111	11	.40
379.	448.	652.	890.	1209.	1555.	1703.	1111111111	11	1.09
89.	96.	114.	134.	157.	184.	196.	1111111111	11	.35
72.	79.	100.	119.	140.	163.	173.	1111111111	11	1.00
72.	79.	100.	119.	140.	163.	173.	1111111111	11	.39
72.	79.	100.	119.	140.	163.	173.	1111111111	11	1.00
71.	85.	128.	178.	247.	336.	373.	1111111111	11	1.2[illegible]
52.	59.	81.	107.	141.	181.	198.	1111111111	11	.9[illegible]
18.	22.	37.	52.	77.	109.	124.	1111111111	11	.4[illegible]
16.	17.	19.	21.	24.	26.	27.	1111111111	11	.40
28.	31.	42.	55.	73.	94.	103.	1111111111	11	.40
1217.	1416.	2003.	2727.	3572.	4568.	5025.	1111111111	11	.68
1217.	1416.	2003.	2727.	3572.	4574.	5009.	1111111111	11	.68
29.	37.	59.	86.	124.	171.	191.	1111111111	11	.87
539.	627.	888.	1209.	1583.	2029.	2222.	1111111111	11	1.09
13.	13.	16.	20.	24.	29.	31.	1111111111	11	.39
11.	11.	21.	40.	70.	122.	161.	1111111111	11	12.97
1.	1.	1.	2.	2.	3.	4.	1111111111	11	28.13
346.	392.	526.	676.	865.	1078.	1169.	1111111111	0	2.73
12.	13.	15.	17.	20.	23.	24.	1111111111011100		.45
194.	224.	316.	422.	563.	723.	792.	111111	0	1.35
194.	224.	316.	422.	563.	723.	792.	111111	0	2.14
16.	19.	28.	39.	53.	72.	80.	111111	0	2.25
104.	115.	147.	188.	241.	308.	338.	1111111111001100		.65
55.	61.	79.	100.	127.	161.	176.	1111111111001100		1.61
11.	13.	15.	18.	21.	25.	27.	1111111111001100		4.73
13.	13.	16.	19.	23.	27.	29.	1111111111001100		4.73
12.	12.	15.	17.	20.	23.	25.	1111111111001100		2.37
14.	16.	22.	28.	36.	45.	49.	1111111111	0	5.44
1871.	2118.	2849.	3663.	4689.	5845.	6337.	1111111111	0	1.[illegible]
19.	22.	31.	41.	55.	70.	77.	1111000000	0	1.[illegible]
15.	17.	24.	30.	39.	51.	56.	1111000000	0	4.[illegible]
30.	35.	49.	65.	86.	114.	126.	1110000000	0	1.0[illegible]
21.	22.	26.	29.	34.	39.	41.	1111000000	0	1.54
85.	89.	102.	117.	135.	155.	164.	1111000000	0	1.[illegible]
18.	20.	28.	35.	45.	58.	64.	1110000000	0	1.23
18.	20.	28.	35.	45.	58.	64.	1110000000	0	1.0[illegible]

APPENDIX E

SAMPLE OUTPUT

Below is the output file generated by the program source file displayed above using the data input file also displayed above. The first section of the output file displays the system parameters used in the input file.

The remaining portions of the output file show the year of analysis, the number of iterations to find an equilibrium, and the equilibrium found. the last line of each section shows the total transportation benefits attributable to the system with traffic demands as shown in the input file.

```
-GE1RUN
12.14.00. ATTN: ADP COORD. AND ALL USERS
12.14.00. DELIVERY ORDER AND CONVERSION INFO FOR CDC
12.14.00. HOTNEWS/UN=CECELB 22JUL83

  1  .725 53500.
  2  .725 53500.
  3  .725 53500.
  4  .725 53500.
  5  .725 53500.
  6  .725 53500.
  7  .725 53500.
  8  .725 53500.
  9  .725 53500.
 10  .725 53500.
 11  .725 53500.
 12  .725 53500.
 13 1.683 23000.
 14  .725 53500.
 15  .725 53500.
 16  .725 53500.

YEAR  1     ITERATIONS    14

  EQUIL           SUPPLY       LAST      MINIMUM      MAXIMUM
  DELAY  LOCK    TONNAGE       INCR      TONNAGE      TONNAGE
  .6362    1      25005.     0.0000       25005.       25005.
  .6362    2      25005.     0.0000       25005.       25005.
  .6362    3      25005.     0.0000       25005.       25005.
  .6331    4      24939.     0.0000       24939.       24939.
  .6264    5      24799.     0.0000       24799.       24799.
  .6264    6      24799.     0.0000       24799.       24799.
  .6070    7      24380.     0.0000       24380.       24380.
  .6070    8      24380.     0.0000       24380.       24380.
  .6070    9      24380.     0.0000       24380.       24380.
  .6070   10      24380.     0.0000       24380.       24380.
  .2219   11      12538.     -.0001       12538.       12538.
  .2681   12      14442.     -.0001       14442.       14442.
 3.3279   13      15275.    -2.4659       15275.       15275.
  .2896   14      15270.     -.0001       15270.       15270.
 1.4679   15      35812.     0.0000       35812.       35812.
 1.2231   16      33590.     0.0000       33590.       33590.
****** TOTAL BENEFITS=     67178.23 ******
```

PROJECT	Page 2 of 4	COMPUTED BY	DATE
SUBJECT		CHECKED BY	DATE

YEAR 2 ITERATIONS 31

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.3073	1	28186.	.0002	27981.	28292.
.3073	2	28186.	.0002	27981.	28292.
.3073	3	28186.	.0002	27981.	28292.
.3073	4	28186.	.0002	27906.	28217.
.3001	5	28067.	0.0000	27756.	28067.
.3001	6	28067.	0.0000	27756.	28067.
.7715	7	27582.	0.0000	27271.	27582.
.7715	8	27582.	0.0000	27271.	27582.
.7715	9	27582.	0.0000	27271.	27582.
.7715	10	27582.	0.0000	27271.	27582.
.2697	11	14506.	0.0000	14506.	14506.
.3301	12	16737.	0.0000	16737.	16737.
5.6887	13	17749.	0.0000	17749.	17749.
.3598	14	17743.	0.0000	17743.	17743.
2.3198	15	40761.	.0002	40694.	41005.
1.8434	16	38398.	.0002	38096.	38407.

****** TOTAL BENEFITS= 72760.74 ******

YEAR 3 ITERATIONS 64

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.8933	1	29532.	-.0043	29532.	29532.
.8933	2	29532.	-.0043	29532.	29532.
.8933	3	29532.	-.0043	29532.	29532.
.8862	4	29427.	0.0000	29427.	29427.
.8741	5	29244.	0.0000	29244.	29244.
.8741	6	29244.	0.0000	29244.	29244.
.8300	7	28557.	0.0000	28557.	28557.
.8300	8	28557.	0.0000	28557.	28557.
.8300	9	28557.	0.0000	28557.	28557.
.8300	10	28557.	0.0000	28557.	28557.
.3371	11	16979.	0.0000	11921.	19316.
.4466	12	20392.	0.0000	14905.	22300.
24.4974	13	21521.	0.0000	16216.	23611.
.5013	14	21869.	0.0000	16208.	23603.
4.8888	15	46591.	0.0000	39306.	46701.
3.0368	16	43189.	0.0000	35835.	43230.

****** TOTAL BENEFITS= 74054.37 ******

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SUBJECT		CHECKED BY	DATE

YEAR 4 ITERATIONS 70

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
1.1926	1	33273.	0.0000	31496.	36950.
1.1926	2	33273.	0.0000	31496.	36950.
1.1926	3	33273.	0.0000	31496.	36950.
1.0722	4	31918.	0.0000	31361.	36815.
1.0420	5	31549.	0.0000	31144.	36598.
1.0420	6	31549.	0.0000	31144.	36598.
1.0020	7	31040.	0.0000	30225.	35679.
1.0020	8	31040.	0.0000	30225.	35679.
1.0020	9	31040.	0.0000	30225.	35679.
1.0020	10	31040.	0.0000	30225.	35679.
.3096	11	16011.	-.0007	16011.	16011.
.4300	12	19918.	-.0009	19918.	19918.
30.4407	13	21795.	-3.5432	21795.	21795.
.4980	14	21785.	-.0010	21785.	21785.
4.1797	15	45592.	0.0000	44935.	50389.
4.1797	16	45592.	0.0000	40307.	45761.

****** TOTAL BENEFITS= 91963.88 ******

YEAR 5 ITERATIONS 235

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
1.3275	1	34602.	0.0000	34063.	39588.
1.3275	2	34602.	0.0000	34063.	39588.
1.3275	3	34602.	0.0000	34063.	39588.
1.3096	4	34436.	0.0000	33887.	39412.
1.2834	5	34188.	0.0000	33624.	39149.
1.2834	6	34188.	0.0000	33624.	39149.
1.1700	7	33031.	0.0000	32397.	37922.
1.1700	8	33031.	0.0000	32397.	37922.
1.1700	9	33031.	0.0000	32397.	37922.
1.1700	10	33031.	0.0000	32397.	37922.
.3097	11	16015.	0.0000	16004.	16015.
.4439	12	20317.	0.0000	20306.	20317.
60.2422	13	22375.	.0310	22371.	22382.
.5210	14	22371.	0.0000	22360.	22371.
6.8269	15	48364.	0.0000	46636.	52161.
3.6679	16	44670.	0.0000	40832.	46357.

****** TOTAL BENEFITS= 81836.15 ******

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SUBJECT		CHECKED BY	DATE

YEAR 6 ITERATIONS 275

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
1.6610	1	37244.	0.0000	36979.	42781.
1.6610	2	37244.	0.0000	36979.	42781.
1.6610	3	37244.	0.0000	36979.	42781.
1.6877	4	37424.	0.0000	36749.	42551.
1.5857	5	36714.	0.0000	36434.	42236.
1.5857	6	36714.	0.0000	36434.	42236.
1.3702	7	34988.	0.0000	34851.	40653.
1.3702	8	34988.	0.0000	34851.	40653.
1.3702	9	34988.	0.0000	34851.	40653.
1.3702	10	34988.	0.0000	34851.	40653.
.3925	11	18791.	0.0000	15178.	18791.
.4447	12	20341.	0.0000	16728.	20341.
82.3289	13	22539.	.3442	19280.	22893.
.5417	14	22880.	0.0000	19267.	22880.
8.4132	15	49255.	0.0000	47708.	53510.
3.5109	16	44343.	0.0000	44248.	50050.

****** TOTAL BENEFITS= 73312.81 ******

YEAR 7 ITERATIONS 261

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
1.4448	1	35624.	0.0000	35459.	39691.
1.4448	2	35624.	0.0000	35459.	39691.
1.4448	3	35624.	0.0000	35459.	39691.
1.4019	4	35264.	0.0000	35205.	39437.
1.4353	5	35546.	0.0000	34867.	39099.
1.4353	6	35546.	0.0000	34867.	39099.
1.2003	7	33354.	0.0000	33131.	37363.
1.2003	8	33354.	0.0000	33131.	37363.
1.2003	9	33354.	0.0000	33131.	37363.
1.2003	10	33354.	0.0000	33131.	37363.
.4253	11	19780.	0.0000	15920.	19780.
.4838	12	21413.	0.0000	17553.	21413.
82.1790	13	22538.	1.2650	20809.	24669.
.6197	14	24656.	0.0000	20796.	24656.
12.2131	15	50502.	0.0000	47035.	51267.
3.3114	16	43890.	0.0000	43381.	47613.

****** TOTAL BENEFITS= 78769.56 ******

APPENDIX F

MATHEMATICAL DESCRIPTION AND PROOF OF SYSTEMIC EQUILIBRIUM

I. The Model

Let L denote the finite set of constraint points in the navigation system. Let M denote the index set of potential commodity movements in the navigation system where a potential commodity movement is defined as an ordered triple (t_m, L_m, ts_m) with t_m denoting the total tons of movement m desirous of transitting the system $(t_m > 0)$ during the time period of analysis, L_m denoting the set of constraint points transitted by movement m if it moves through the system $(L_m \leq L)$, and ts_m denoting the total transportation cost savings of movement m over its next cheapest alternative means of transport (with no delays at system constraint points). Let c_m denote the hourly cost of system delay per ton for movement m. For ease of exposition, we have assumed c_m is equal across system constraint points for movement m. However, this assumption may be relaxed and the results of this paper still hold. Let $h_m = ts_m/c_m$ where h_m is the transportation savings of movement m expressed in units of hourly per ton system delays. Let M^ℓ denote the index set of movements that transit constraint point ℓ if they transit the system, that is, $m \in M^\ell$ if, and only if $m \in M$ and $\ell \in L_m$.

Denote the delay-tonnage relationship at a constraint point ℓ as $d^\ell = f^\ell(t^\ell)$ where d^ℓ is the hours of delay incurred by each ton transitting constraint point ℓ; t^ℓ is the total amount of tonnage transitting constraint point ℓ; and f^ℓ is a one to one, strictly increasing, continuous function defined on $t^\ell \in [0, Cap^\ell]$ where Cap^ℓ is the physical capacity of constraint point ℓ and $f^\ell(0) = 0$. This relationship reflects the notion that increasing levels of tonnage through a constraint point increase the delay incurred by each ton transitting that point.

Note, $f^{\ell-1}$ (d^{ℓ}) is defined for $d^{\ell} \geq 0$ and has the same properties as f.

For each $m \in M$, define the real valued function $nh_m(\vec{d}) = h_m - \sum_{\ell \in L_m} d^{\ell}$ where d is the ordered vector of delays at each system constraint point $(\vec{d} \geq 0)$ and nh_m expresses the net transportation cost savings (in units of hours) of movement m with system constraint points delays equal to $\vec{d}$. nh_m is also a continuous function of $\vec{d}$. Further, $\vec{d}_1 \geq \vec{d}_0$ implies that $nh_m(\vec{d}_0) \geq nh_m(\vec{d}_1)$ and $\vec{d}_1 > \vec{d}_0$ implies $nh_m(\vec{d}_0) > nh_m(\vec{d})$.

For each ℓ, and $\vec{d} \geq \vec{0}$ define the index sets $M^{\ell}n\ (\vec{d}) = \{m \in M^{\ell}:\ nh_m(\vec{d}) \geq 0\}$ and $M^{\ell}p\ (\vec{d}) = \{m \in M^{\ell}:\ nh_m(\vec{d}) \leq 0\}$. $M^{\ell}n\ (\vec{d})$ indicates those movements transitting constraint point ℓ with non-negative net transportation savings at $\vec{d}$, and $M^{\ell}p$ indicates those with non-positive net transportation savings. Let $M^{\ell}i\ (\vec{d}) = M^{\ell}p\ (\vec{d}) \cap M^{\ell}n\ (\vec{d})$. $M^{\ell}i\ (\vec{d}) = \emptyset$ if and only if for all $m \in M^{\ell}$, $nh_m(\vec{d}) \neq 0$.

<u>LEMMA 1:</u> Let $\vec{d}_0 \geq \vec{0}$ and $M^{\ell}i\ (\vec{d}_0) = \emptyset$. There is a $\sigma^{\ell}(\vec{d}_0)$ such that for $\forall \vec{d}_1$ with $|d_1^{\kappa} - d_0^{\kappa}| < \sigma(\vec{d}_0)$, then $M^{\ell}n\ (\vec{d}_1) = M^{\ell}n\ (\vec{d}_0)$ and $M^{\ell}p\ (\vec{d}_1) = M^{\ell}p\ (\vec{d}_0)$.

PROOF: Let $\|L\|$ denote the total number of system constraint points. As $M^{\ell}i\ (\vec{d}_0) = \emptyset$, then for all $m \in M^{\ell}$, $nh_m(\vec{d}_0) \neq 0$. Let $\sigma(\vec{d}_0) = \min^{\ell}_{m \in M}\{|\ nh_m(\vec{d}_0)|/\|L\|\}$. $\sigma^{\ell}(\vec{d}_0) > 0$. Let $\vec{d}_1$ be such that $|d_1^{\kappa} - d_0^{\kappa}| < \sigma^{\ell}(\vec{d}_0)$. Then $\sum_{K \in L_m} |d_1^{\kappa} - d_0^{\kappa}| \leq \sum_{K \in L} |d_1^{\kappa} - d_0^{\kappa}| < \min_{m \in M^{\ell}} \{|\ nh_m(\vec{d}_0)|\}$ for all $m \in M^{\ell}$. Hence,

$|nh_m(\vec{d}_0) - nh_m(\vec{d}_1)| < \min^{\ell}_{m \in M} \{|nh_m(\vec{d}_0)|\} \leq |nh_m(\vec{d}_0)|$. Let $m_1 \in M^{\ell}n\ (\vec{d}_0)$. Then, $nh_{m_1}(\vec{d}_1) > 0$ and we have $nh_{m_1}(\vec{d}_0) - nh_{m_1}(\vec{d}_1) < nh_{m_1}(\vec{d}_0)$. Rearranging yields $nh_{m_1}(\vec{d}_1) \gtrless 0$ and $m_1 \in M^{\ell}n(\vec{d}_1)$. Similarly, let $m_2 \in M^{\ell}p\ (\vec{d}_0)$. Then $nh_{m_2}(\vec{d}_0) < 0$ and we have $nh_{m_2}(\vec{d}_1) - nh_{m_2}(\vec{d}_0) < -nh_{m_2}(\vec{d}_0)$. Rearranging yields $nh_{m_2}(\vec{d}_1) < 0$ and $m_2 \in M^{\ell}p(\vec{d}_1)$. Now as $M^{\ell}i\ (\vec{d}_0) = \emptyset$, then $M^{\ell}/M^{\ell}n(\vec{d}_0) = M^{\ell}p(\vec{d}_0)$. We have shown $M^{\ell}p(\vec{d}_1)$ $\supseteq M^{\ell}_{np}(\vec{d}_0)$ and $M^{\ell}/M^{\ell}p(\vec{d}_1) \supseteq M^{\ell}/M^{\ell}p(\vec{d}_0)$. Hence, $M^{\ell}p(\vec{d}_1) = M^{\ell}p(\vec{d}_0)$ and $M^{\ell}n(\vec{d}_1) = M^{\ell}n(\vec{d}_0)$. (Q.E.D.)

LEMMA 2: Let $\vec{d}_0 \geq \vec{0}$ and $Mi^{\ell}(\vec{d}_0) \neq \emptyset$. There is a $\delta^{\ell}(\vec{d}_0)$ such that for $\vec{d}_1$, with $|d_1^{\kappa} - d_0^{\kappa}| < \delta^{\ell}(\vec{d}_0)$, then $Mnp^{\ell}(\vec{d}_0) \supseteq Mnp^{\ell}(\vec{d}_1)$ and $Mnn^{\ell}(\vec{d}_0) \supseteq Mnn^{\ell}(\vec{d}_1)$.

PROOF: Let $M^{\ell}/Mi^{\ell}(\vec{d}_0) \neq \emptyset$. Then let $\delta^{\ell}(\vec{d}_0) = \min_{m \in M^{\ell}/Mi^{\ell}(\vec{d}_0)} \{|nh_m(\vec{d}_0)|\} / ||L||$. Then following the proof of LEMMA 1 above, if $m \in [M^{\ell}/Mi^{\ell}(\vec{d}_0)] \cap Mnn^{\ell}(\vec{d}_0)$, then $m \in [M^{\ell}/Mi^{\ell}(\vec{d}_1)] \cap Mnn^{\ell}(\vec{d}_1)$. Note that $[M^{\ell}/Mi^{\ell}(\vec{d})] \cap Mnn^{\ell}(\vec{d}) = M^{\ell}/Mnp^{\ell}(\vec{d})$ for all $\vec{d}$. Consequently, we have $M^{\ell}/Mnp^{\ell}(\vec{d}_1) \supseteq M^{\ell}/Mnp^{\ell}(\vec{d}_0)$, and hence, $Mnp^{\ell}(\vec{d}_0) \supseteq Mnp^{\ell}(\vec{d}_1)$.

Similarly, we have $[M^{\ell}/Mi^{\ell}(\vec{d}_1)] \cap Mnp^{\ell}(\vec{d}_1) \supseteq [M^{\ell}/Mi^{\ell}(\vec{d}_0)] \cap Mnp^{\ell}(\vec{d}_0)$, which in turn yields $M^{\ell}/Mnn^{\ell}(\vec{d}_1) \supseteq M^{\ell}/Mnn^{\ell}(\vec{d}_0)$. Hence, $Mnn^{\ell}(\vec{d}_0) \supseteq Mnn^{\ell}(\vec{d}_1)$. The lemma is immediate when $M^{\ell}/Mi^{\ell}(\vec{d}_0) = \emptyset$. (Q.E.D.)

Define the demand correspondence at constraint point ℓ for all $\vec{d} \geq 0$ to be $t^{\ell}(\vec{d}) = \{t \in \mathbb{R}^1: t \ni [t^{\ell}b(\vec{d}), \min\{t^{\ell}u(\vec{d}), Cap^{\ell}]$ where $tu^{\ell}(\vec{d}) = \sum_{m \in M^{\ell}_{nn(\vec{d})}} \sum tm$ for $Mnn^{\ell}(\vec{d}) \neq \emptyset$, $tu^{\ell}(\vec{d}) = 0$ for $Mnn^{\ell}(\vec{d}) = \emptyset$. $t^{\ell}b = \sum_{m \in M^{\ell}/Mnp^{\ell}(\vec{d})} tm$ for $M^{\ell}/Mnp^{\ell}(\vec{d}) \neq 0$, $t_b^{\ell} = 0$ for $M^{\ell}/Mnp^{\ell}(\vec{d}) = \emptyset$. Now as $Mnn^{\ell}(\vec{d}) \supseteq M^{\ell}/Mnp^{\ell}(\vec{d})$ for all d, the demand correspondence is well defined.

REMARK 1: $t^{\ell}(\vec{d})$ is single-valued at $\vec{d}$ if and only if for all $m \in M^{\ell}$, $nh_m(\vec{d}) \neq 0$.

REMARK 2: $t^{\ell}(\vec{d})$ is non-empty for all $\vec{d} \geq 0$.

REMARK 3: For all $\vec{d} \geq \vec{0}$, $t^{\ell}(\vec{d})$ is a closed, bounded, convex subset of $\mathbb{R}^1$/ Further, for all $\vec{d}$, $t^{\ell}(\vec{d})$ is compact.

REMARK 4: The range of $t^{\ell}(\vec{d}) = [0, t^{\ell}u(\vec{0})]$ is closed, bounded, and hence compact. Further, $t \in [0, t_u^{\ell}(\vec{0})]$ imples $t \in t^{\ell}(\vec{d})$ for some $\vec{d} \geq \vec{0}$.

REMARK 5: $Mnn^{\ell}(\vec{d}_0) \supseteq Mnn^{\ell}(\vec{d}_1)$ implies $t_u^{\ell}(\vec{d}_0) \geq t_u^{\ell}(\vec{d}_0)$ and $Mnp^{\ell}(\vec{d}_0) \supseteq Mnp^{\ell}(\vec{d}_1)$ implies $t_b^{\ell}(\vec{d}_0) \leq t_b^{\ell}(\vec{d}_1)$.

LEMMA 3: The demand correspondence $t^{\ell}(\vec{d})$ is upper semi-continuous.

PROOF: Let $\{\vec{d}_j\}$ be a sequence with $\vec{d}_j \geq 0$ such that $\vec{d}_j \to \vec{d}_0 \geq 0$. Let $\{t_j\}$ be a sequence with $0 \leq t_j \leq \min \{t_u^{\ell}(o), Cap^{\ell}\}$ with $t_j \in t^{\ell}(d_j)$ and $t_j \to t_o$. We need to show $t_0 \in t^{\ell}(\vec{d}_0)$.

Lemma 1 and Lemma 2 guarantee the existence of a $\delta^{\ell}(\vec{d}_0)$ such that for $/d_j^{\ k} - d_0^{\ k}/ < \delta^{\ell}(\vec{d}_0)$, then $M\hat{n}n^{\ell}(\vec{d}_0) \supseteq M\hat{n}n^{\ell}(\vec{d}_j)$ and $M\hat{n}p^{\ell}(\vec{d}_0) \supseteq M\hat{n}p^{\ell}(\vec{d}_j)$. Now, as $\vec{d}_j \to \vec{d}_0$, there must exist some $\hat{j}$ such that $\vec{d}_j \in \delta^{1}(\vec{d}_0)$ for all $j \geq \hat{j}$. Hence, $M\hat{n}n^{\ell}(\vec{d}_o) \supseteq M\hat{n}n^{\ell}(\vec{d}_j)$ and $M^{\ell}/M\hat{n}p^{\ell}(\vec{d}_0) \subseteq M^{\ell}/M\hat{n}p^{\ell}(\vec{d}_j)$ for all $j \geq \hat{j}$. Consequently, $t^{\ell}(\vec{d}_0) \supseteq t^{\ell}(\vec{d}_j)$ for all $j \geq \hat{j}$. Hence, $t_j \in t^{\ell}(\vec{d}_0)$ for all $j \geq \hat{j}$ and as $t^{\ell}(\vec{d}_0)$ is closed $t^0 \in t^{\ell}(\vec{d}_0)$. (Q.E.D.)

The demand correspondence is based upon the notion that if a potential system movement has positive net transportation cost savings at system delay levels, then that movement will move on the system. Movements with "0" net transportation cost savings at system delay levels are indifferent to transitting the system and may or may not, either entirely or partly, move on the system. Movements with negative transportation cost savings at system delay levels will not move on the system as they enjoy a cheaper alternative means of transport.

Define $\vec{t}$ to be the ordered vector of tonnage transitting system constraint points. That is, $\vec{t} = (t^1, t^2, t^3, \ldots, t^{||L||-1}, t^{||L||})$.

Define a system equilibrium to be $(\vec{t}*, \vec{d}*)$ such that for all $\ell \in L$, $t^{\ell}(\vec{d}*) \xi \neq^{\ell-1} (\vec{d}*)$. The next section of this paper provides a proof that in any navigation system as modelled above, there is such a $(\vec{t}*, \vec{d}*)$.

PROOF OF EXISTENCE OF A SYSTEMIC EQUILIBRIUM

Define the set $T \subseteq R^{||L||}$ to be $\underset{\ell \in L}{X}$ $[0, \min \{t_u^\ell(\vec{0}), Cap^\ell\}]$

REMARK 6: As the finite Cartesian product of compact sets, T is compact.

REMARK 7: As $M \neq \emptyset$, then T is non-empty.

REMARK 8: As $[0, \min \{t_u^\ell(\vec{0}), Cap^\ell\}]$ is convex for all ℓ so also is T convex.

Define the correspondence $tt(\vec{d})$: $\{\vec{d}: \vec{d} \geq 0\} \to T$ such that $tt^\ell(\vec{d}) = t^\ell(\vec{d})$.

REMARK 9: $tt(\vec{d})$ is upper semi-continuous as the finite Cartesian product of upper semi-continuous correspondences.

REMARK 10: The set $tt(\vec{d}_0)$ is convex as the finite Cartesian product of the convex sets $t^\ell(\vec{d}_0)$ for all $\vec{d}_0 \geq \vec{0}$.

REMARK 11: The set $tt(\vec{d}_0)$ is non-empty as the finite Cartesian product the non-empty sets $t^\ell(\vec{d}_0)$ for all $\vec{d}_0$.

Define the function $\mathfrak{z}(\vec{t})$: $T \to \{d: \vec{d} \geq 0\}$ such that $\mathfrak{z}^\ell(\vec{t}) = f^\ell(t^\ell)$.

REMARK 12: $\mathfrak{z}(\vec{t})$ is continuous as the finite Cartesian product of continuous function $f^\ell(t^\ell)$.

✓ REMARK 13: $\mathfrak{z}(\vec{t})$ is onto $\{d: \vec{d} \geq 0$ as $f^\ell(t^\ell)$ is onto $[0, \infty]\}$.

REMARK 14: $\mathfrak{z}(\vec{t})$ is one to one and defined for all $\vec{t} \in T$.

Let $h = tt \circ \mathfrak{z}$: $T \to T$, that is, h is a correspondence from T into T.

REMARK 15: $h(\vec{t})$ is upper semi-continuous as the composition of a upper semi-continuous correspondence with a continuous function.

REMARK 16: $h(\vec{t})$ is non-empty for all $\vec{t} \in T$ as $\mathfrak{z}(\vec{t})$ is defined for all

✓ $\vec{t} \in T$, $\mathfrak{z}^\ell(\vec{t}) = f^\ell(\vec{t}) = f^\ell(t^\ell) \in [0, \infty]$, $tt(\vec{d})$ is defined for all $\vec{d} \geq \vec{0}$, and $tt(\vec{d})$ is non-empty for all $\vec{d} \geq \vec{0}$.

REMARK 17: $h(\vec{t})$ is convex for all t as $tt(\vec{d})$ is convex for all $\vec{d} \geq \vec{0}$.

<u>THEOREM 1:</u> There exists some $\vec{t}^*$ such that $\vec{t}^* \in T$ and $\vec{t}^* \in \Xi(t^*)$.

PROOF: As T is non-empty, compact, convex subset of $\mathbb{R}^{||L||}$ and h is an upper semi-continuous function from T into itself such that for all $\vec{t} \in T$, $h(\vec{t})$ is non-empty and convex. Then by Kakutani's* Fixed Point Theorem, there is some $\vec{t}^* \in T$ such that $t^* \in h(\vec{t}^*)$. (Q.E.D.)

Let $\vec{d}^* = \Xi(\vec{t}^*)$ which implies, for all $\ell \in L$, that $d^{*\ell} = f^{\ell}(t^{*\ell})$.

<u>THEOREM 2:</u> $(\vec{t}^*, \vec{d}^*)$ is a system equilibrium.

PROOF: $\vec{t}^* \in h(\vec{t}^*)$ is equivalent to $\vec{t}^* \in tt(\Xi(\vec{t}^*))$. Now, $d^{*\ell} = f^{\ell}(t^{*\ell})$ for all ℓ. Consequently, $\vec{t}^{*\ell} = f^{\ell-1}(d^{*\ell}) \in tt^{\ell}(\Xi(\vec{t}^*))$ and $tt^{\ell} = t^{\ell}(\vec{d}^*)$. Hence, $\vec{t}^{*\ell} \in t^{\ell}(\vec{d}^*)$ and $f^{\ell-1}(d^{*\ell}) \in t^{\ell}(\vec{d}^*)$ for all $\ell \in L$. (Q.E.D.)

<u>REMARK 18:</u> A system may have more than one equilibrium. Consider a navigation system with 3 identical constraint points with $f^{\ell}(t^{\ell}) = t^{\ell}$, $\ell =$ 1, 2, 3, defined on $t^{\ell} \in [0, 6]$, $\ell =$ 1, 2, 3. Further, suppose this system has 6 potential movements described as follows:

<u>MOVEMENT</u>	<u>TONS</u>	L_m	GH_m
1	1	{1}	4
2	1	{1, 2}	5
3	2	{1, 2, 3}	7
4	1	{2, 3}	5
5	1	{2}	4
6	1	{3}	4

It is easy to verify that this system has many possible equilibria. For example, $\vec{t} = (2,3,2)$ and $\vec{d} + (2, 2\ 2/3, 2\ 1/3)$ is an equilibrium. Also, $\vec{t} = (2, 2\ 2/3, 2\ 1/3)$ and $\vec{d} = (2, 2/3, 2\ 1/3)$ is an equilibrium. In fact, this system has infinitely many equilibria. Any $\vec{t}$ with $t^1 + t^2 + t^3 = 7$ and, either, $t^1 + t^2 + t^3 = 5$ yields an equilibrium.

Consequently, whenever a system has multiple equilibria, traffic patterns are indeterminant. However, in practice, this is an unlikely event. Most navigation systems are characterized by many movements with many different transportation cost savings with relatively few origin and destination patterns for the majority of tonnage desirous of moving on the system. This reduces the chances of multiple equilibria. However, if multiple equilibria do exist, all is not lost.

REMARK 19: Let $Mnn(\vec{d}) = \{m \in M: \; nh_m(\vec{d}) \geq 0\}$. Let $(\vec{t}*_1, \vec{d}*_1)$ and $(\vec{t}*_2, \vec{d}*_2)$ be system equilibria. Then $\sum_{m \in Mnn(\vec{d}_1)} nh_m(\vec{d}*_1) \cdot t_m = \sum_{m \in Mnn(\vec{d}_2)} nh_m(\vec{d}*_2) \cdot t_m$.

That is, at any systemic equilibrium, the net system benefits are constant. Hence, though the traffic patterns may be indeterminant, the total system benefits are not (the total net system transportation cost savings are the same for all equilibria).

APPENDIX G

TEST CASE

Test Case

This section demonstrates the advantage of using a systemic model to evaluate the NED benefits of navigation improvements. First, estimate the benefits of replacing a lock in a system totally ignoring system effects. That is, the lock is analyzed as if it is the only lock in the system affected by a change in its operating characteristics (in this example an increase in capacity)., Then compare these results to the NED benefits computed using the General Equilibrium Model and the same traffic demands and capacity increase. The single lock in isolation analysis overestimates NED benefits by approximately 55%, apparently because system wide impacts of the capacity increase are ignored. The system used in the analysis will consist of 16 locks. To make the analysis as simple as possible, only the locks are considered to be system constraint points. Further, with one exception, all locks are estimated to have an annual capacity of approximately 53.5 million tons. The capacity of the exception is estimated at 23 million tons. The NED benefits of expanding the capacity of this one lock to 53.5 million tons annually are estimated using both of the approaches outlined above.

The traffic demands on the system are shown in the input file described in Appendix C. These demands are used only to demonstrate the importance of systems analysis; they do not represent current traffic forecasts or rate savings data and no relationship to current conditions is intended or warranted.

PROJECT	Page __ of __	COMPUTED BY	DATE
SUBJECT TABLE I		CHECKED BY	DATE

CAPACITY = 23 MILLION TONS

ONE LOCK ANALYSIS

LK	K(L)	CAP
1	1.683	23000.

YEAR 1 ITERATIONS 3

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
3.3305	1	15279.	-3.4111	15279.	15279.

****** TOTAL BENEFITS= 76380.07 ******

YEAR 2 ITERATIONS 3

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
5.7141	1	17767.	-1.0275	17767.	17767.

****** TOTAL BENEFITS= 87277.72 ******

YEAR 3 ITERATIONS 10

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
33.7079	1	21906.	2.5281	16216.	23611.

****** TOTAL BENEFITS= 94564.59 ******

YEAR 4 ITERATIONS 10

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
33.7079	1	21906.	2.5281	21838.	31549.

****** TOTAL BENEFITS= 127194.53 ******

YEAR 5 ITERATIONS 23

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
71.9101	1	22474.	1.6854	22371.	26104.

****** TOTAL BENEFITS= 126704.55 ******

YEAR 6 ITERATIONS 28

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
87.6404	1	22567.	3.9326	19473.	22958.

****** TOTAL BENEFITS= 144004.04 ******

YEAR 7 ITERATIONS 28

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
87.6404	1	22567.	3.9326	21451.	25163.

****** TOTAL BENEFITS= 160174.93 ******

PROJECT	Page __ of __	COMPUTED BY	DATE
SUBJECT TABLE 2		CHECKED BY	DATE

CAPACITY = 53.5 MILLION TONS

ONE LOCK ANALYSIS

LK	K(L)	CAP
1	.725	53500.

YEAR 1 ITERATIONS 3

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.2898	1	15279.	-6.4518	15279.	15279.

****** TOTAL BENEFITS= 78033.98 ******

YEAR 2 ITERATIONS 3

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.3605	1	17767.	-6.3811	17767.	17767.

****** TOTAL BENEFITS= 90663.91 ******

YEAR 3 ITERATIONS 3

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.5897	1	23996.	-6.1519	23996.	23996.

****** TOTAL BENEFITS= 122702.57 ******

YEAR 4 ITERATIONS 3

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
1.0830	1	32047.	-5.6586	32047.	32047.

****** TOTAL BENEFITS= 164218.61 ******

YEAR 5 ITERATIONS 3

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
2.1664	1	40085.	-4.5752	40085.	40085.

****** TOTAL BENEFITS= 207714.95 ******

YEAR 6 ITERATIONS 3

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
6.5948	1	48201.	-.1468	48201.	48201.

****** TOTAL BENEFITS= 248515.60 ******

YEAR 7 ITERATIONS 10

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
27.3209	1	52117.	-3.8589	52117.	52117.

****** TOTAL BENEFITS= 235600.80 ******

Tables 1 and 2 display the results of the NED computations as if there were only one lock in the system. Table 1 shows year by year NED benefits for lock of capacity equal to 23 million tons annually. The years of analysis are 1984, 1990, 2000, 2010, 2020, 2030, 2034 respectively. Table 2 shows year by year NED benefits with lock capacity equal to 53.5 million annual tons. Table 3 below summarizes these results.

TABLE 3
Benefits in K$
(One Lock Alone Approach)
Capacity

YEAR	23000	53500	INCREASE IN BENEFITS
1984	76380	78034	1654
1990	87278	90664	3386
2000	94565	122703	28138
2010	127195	164219	37024
2020	126705	207715	81010
2030	144004	248516	104512
2034	160175	235601	75426
		Net Present Value =	250065

Smoothing these values over the 50 year period of analysis and discounting at 7-7/8% yields a net present value of approximately $250 million as a measure of the incremental NED benefits if measured using only the effects at one lock.

Now, using exactly the same input data and traffic demands and analyzing the lock as a component of a system (accounting for changes elsewhere in the system as a result of the capacity increase) yields the following data. Tables 4 and 5 display the results of the NED computations as computed by the general equilibrium model and accounting for system-wide effects.

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SUBJECT TABLE 4		CHECKED BY	DATE

CAPACITY OF LOCK 13 INCREASED TO 53.5 MILLION TONS

SYSTEMS ANALYSIS

1
1
1

1	.725	53500.
2	.725	53500.
3	.725	53500.
4	.725	53500.
5	.725	53500.
6	.725	53500.
7	.725	53500.
8	.725	53500.
9	.725	53500.
10	.725	53500.
11	.725	53500.
12	.725	53500.
13	.725	53500.
14	.725	53500.
15	.725	53500.
16	.725	53500.

YEAR 1 ITERATIONS 8

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.6362	1	25005.	-.0066	25005.	25005.
.6362	2	25005.	-.0066	25005.	25005.
.6362	3	25005.	-.0066	25005.	25005.
.6331	4	24939.	-.0066	24939.	24939.
.6264	5	24799.	-.0066	24799.	24799.
.6264	6	24799.	-.0066	24799.	24799.
.6070	7	24380.	-.0067	24380.	24380.
.6070	8	24380.	-.0067	24380.	24380.
.6070	9	24380.	-.0067	24380.	24380.
.6070	10	24380.	-.0067	24380.	24380.
.2220	11	12542.	0.0000	12542.	12542.
.2682	12	14446.	0.0000	14446.	14446.
.2898	13	15279.	0.0000	15279.	15279.
.2897	14	15274.	0.0000	15274.	15274.
1.4684	15	35816.	-.0035	35816.	35816.
1.2235	16	33594.	-.0045	33594.	33594.

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TABLE 4 (Continued)

YEAR 2 ITERATIONS 133

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.8145	1	28305.	.0008	27994.	28305.
.8145	2	28305.	.0008	27994.	28305.
.8145	3	28305.	.0008	27994.	28305.
.8099	4	28230.	0.0000	27919.	28230.
.8009	5	28080.	0.0000	27769.	28080.
.8009	6	28080.	0.0000	27769.	28080.
.7636	7	27443.	.0008	27284.	27595.
.7636	8	27443.	.0008	27284.	27595.
.7636	9	27443.	.0008	27284.	27595.
.7636	10	27443.	.0008	27284.	27595.
.2698	11	14511.	0.0000	14511.	14511.
.3306	12	16755.	0.0000	16755.	16755.
.3605	13	17767.	0.0000	17767.	17767.
.3603	14	17761.	0.0000	17761.	17761.
2.3691	15	40964.	.0008	40699.	41010.
1.8001	16	38139.	.0008	38101.	38412.

****** TOTAL BENEFITS= 76121.17 ******

YEAR 3 ITERATIONS 43

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.9043	1	29694.	0.0000	28706.	29694.
.9043	2	29694.	0.0000	28706.	29694.
.9043	3	29694.	0.0000	28706.	29694.
.8972	4	29589.	0.0000	28601.	29589.
.8848	5	29406.	0.0000	28418.	29406.
.8848	6	29406.	0.0000	28418.	29406.
.8402	7	28719.	0.0000	27731.	28719.
.8402	8	28719.	0.0000	27731.	28719.
.8402	9	28719.	0.0000	27731.	28719.
.8402	10	28719.	0.0000	27731.	28719.
.4165	11	19521.	0.0000	19521.	19521.
.5275	12	22532.	0.0000	22532.	22532.
.5894	13	23990.	0.0000	23990.	23990.
.5890	14	23982.	0.0000	23982.	23982.
4.6991	15	46349.	.0896	45930.	46918.
3.1333	16	43447.	0.0000	42459.	43447.

****** TOTAL BENEFITS= 94187.44 ******

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TABLE 4 (Continued)

YEAR 4 ITERATIONS 117

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.9340	1	30120.	0.0000	26565.	30777.
.9340	2	30120.	0.0000	26565.	30777.
.9340	3	30120.	0.0000	26565.	30777.
.9268	4	30018.	0.0000	26430.	30642.
.9154	5	29855.	0.0000	26213.	30425.
.9154	6	29855.	0.0000	26213.	30425.
.8691	7	29168.	0.0000	25294.	29506.
.8691	8	29168.	0.0000	25294.	29506.
.8691	9	29168.	0.0000	25294.	29506.
.8691	10	29168.	0.0000	25294.	29506.
.6849	11	25990.	0.0000	25990.	25990.
.9195	12	29914.	-.1771	29914.	29914.
1.0773	13	31979.	-.1769	31979.	31979.
1.0765	14	31969.	-.1769	31969.	31969.
9.3677	15	49838.	0.0000	49778.	53990.
4.1297	16	45510.	0.0000	45150.	49362.

****** TOTAL BENEFITS= 112376.50 ******

YEAR 5 ITERATIONS 145

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.6652	1	25599.	.0240	15455.	25889.
.6652	2	25599.	.0240	15455.	25889.
.6652	3	25599.	.0240	15455.	25889.
.6551	4	25396.	.0240	15279.	25713.
.5728	5	23612.	.0240	15016.	25450.
.5728	6	23612.	.0240	15016.	25450.
.5998	7	24223.	0.0000	13789.	24223.
.5998	8	24223.	0.0000	13789.	24223.
.5998	9	24223.	0.0000	13789.	24223.
.5998	10	24223.	0.0000	13789.	24223.
1.1149	11	32419.	0.0000	32419.	32419.
1.6653	12	37273.	0.0000	37273.	37273.
2.1403	13	39963.	0.0000	39963.	39963.
2.1380	14	39952.	0.0000	39952.	39952.
16.2567	15	51216.	.0240	44236.	54670.
7.6039	16	48843.	.0240	38432.	48866.

****** TOTAL BENEFITS= 120512.41 ******

TABLE 4 (Continued)

YEAR 6 ITERATIONS 154

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
1.0398	1	31521.	-.0001	19567.	32934.
1.0398	2	31521.	-.0001	19567.	32934.
1.0398	3	31521.	-.0001	19567.	32934.
1.0195	4	31266.	-.0001	19337.	32704.
.9925	5	30916.	-.0001	19022.	32389.
.9925	6	30916.	-.0001	19022.	32389.
.8843	7	29398.	-.0001	17439.	30806.
.8843	8	29398.	-.0001	17439.	30806.
.8843	9	29398.	-.0001	17439.	30806.
.8843	10	29398.	-.0001	17439.	30806.
1.5622	11	36541.	.0001	24305.	38648.
3.3044	12	43874.	.0001	30067.	44410.
4.2236	13	45662.	.0001	33406.	47749.
4.2224	14	45660.	.0001	33393.	47736.
15.3430	15	51086.	.0001	39203.	66913.
5.0522	16	46786.	-.0001	32258.	59968.

****** TOTAL BENEFITS= 140748.04 ******

YEAR 7 ITERATIONS 207

EQUIL DELAY	LOCK	SUPPLY TONNAGE	LAST INCR	MINIMUM TONNAGE	MAXIMUM TONNAGE
.4827	1	21384.	-.0241	21384.	21384.
.4827	2	21384.	-.0241	21384.	21384.
.4827	3	21384.	-.0241	21384.	21384.
.4733	4	21130.	-.0241	21130.	21130.
.4609	5	20792.	-.0241	20792.	20792.
.4609	6	20792.	-.0241	20792.	20792.
.4011	7	19056.	-.0241	19056.	19056.
.4011	8	19056.	-.0241	19056.	19056.
.4011	9	19056.	-.0241	19056.	19056.
.4011	10	19056.	-.0241	19056.	19056.
1.4830	11	35933.	0.0000	26110.	41825.
1.8937	12	38688.	0.0000	32268.	47983.
2.3421	13	40854.	0.0000	36452.	52167.
2.3404	14	40846.	0.0000	36439.	52154.
14.3778	15	50932.	0.0000	42930.	58645.
11.2708	16	50267.	0.0000	35564.	51279.

****** TOTAL BENEFITS= 160279.76 ******

Table 4 shows NED measurements with capacity increased to 53.5 million annual tons. The lock in question is lock 13. The sample output in Appendix D shows the model output with lock 13 capacity equal to its existing level of 23 million tons annually. Table 5 below summarizes these results.

TABLE 5
Benefits in K$
(System Approach)
Capacity

YEAR	23000	53500	INCREASE IN BENEFITS
1984	67178	68829	1651
1990	72761	76121	360
2000	74054	94187	20133
2010	91964	112376	20412
2020	81836	120512	38676
2030	73313	140748	67435
2040	78770	160280	81510
		Net Present Value =	161325

Smoothing these figures over the 50 year period of analysis yields a net present value of approximately $161 million using a 7-7/8% discount rate. This compares with a figure of $250 million if system effects are ignored. Consequently, using identical traffic demand data, an identical capacity increase, and ignoring system effects overstates the NED benefits of this particular navigation improvement by over 55%. Further, this is a relatively uncongested system for the early years of analysis. In a relatively congested system the overstatement of benefits would be even greater leading to possible erroneous investment decisions.

A NONLINEAR PROGRAMMING MODEL TO MEASURE THE ECONOMIC IMPACTS OF INLAND NAVIGATION SYSTEMS

GEM 2

by

Don Sweeney

U.S. Army Engineer District, St. Louis
Corps of Engineers
St. Louis, Missouri

and

Michael Healy

Boeing Computer Services
Tukwila, Washington

for

Navigation Analysis Center
Institute for Water Resources
U.S. Army Corps of Engineers
Ft. Belvoir, Virginia

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A. Computer Resources Required for Model Execution

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REFERENCES

1. Introduction

This report presents a nonlinear programming model for evaluating the economics of inland waterways navigation systems. The nonlinear program model makes explicit use of the inter-relationships between system components and can evaluate the system-wide impacts of alternative policy measures. It is more efficient for computer time than earlier versions of the general equlibrium model (SWEENEY,[2]) and provides some economic information about the various capacity constraints in the waterways system.

The model is based on the analysis presented in GIOCOECHEA, et al. [1] and SWEENEY [2]. The navigation system is modeled by a group of mathematical equations. These equations depict the relationship between congestion levels at locks in the system and the traffic levels at those locks. The traffic demands at each lock are represented by a group of linear constraints relating individual traffic movements to the locks transitted. Finally, the economic benefit of the entire system is measured at the sum of individual movement benefits net of congestion costs incurred at locks transitted.

With this basis, a linearly constrained, nonlinear maximization formulation is developed to identify the economically optimal level of system usage (maximization of system economic benefits). A similar formulation generates the equilibrium level of system usage based on average congestion costs as defined in SWEENEY [2]. Both formulations are computed using an application of Stanford University's MINOS algorithim in MURTAGH, et al [3], which provides fast, accurate solutions to the associated nonlinear programs.

The range of policy issues which can be addressed by the model include: (1) The national economic development (NED) benefits of capacity expansion measures with all system-wide effects measured. (2) the evaluation of congestion fees so they can be designed to operate the navigation system more efficiently. (3) Combinations of measures evaluated on a system-wide basis with explicit measurement of total system NED changes and (4) user charge design and evaluation. These analyses require an independent (exogenous) projection of traffic between origins and destinations, the delay function for each lock, and tow configuration (and loading). Therefore, the equilibrium

sought does not allow for feed back adjustments in traffic, delay functions, and tow size (or loading).

2. THE MATHEMATICAL MODEL FOR THE ECONOMIC OPTIMUM

A waterway system is given, having L locks and M commodity movements to be assigned a transportation mode, i.e., the waterway system or an alternative mode. The nonlinear programming model presented in this section finds a mode assignment which maximizes the net rate savings (NRS) function over the entire system. The optimal mode assignment is represented by the nonlinear programming solution values of a set of L + M variables z_k ($k = 1, \ldots, n$; $n = L + M$). The first L variables, z_j ($j = 1, \ldots, L$), represent the fraction of lock j's capacity occupied in shipping the movement tonnages. The next M solution variables, z_{L+i} ($i = 1, \ldots, M$), represent the fractions of the total movement i tonnages that move through the waterway system. If w_i is the total tonnage of movement i to be moved during the time period of analysis, then $w_i z_{L+i}$ is the tonnage that moves via waterway. If D_j is the total tonnage capacity for lock j, then $D_j z_j$ is the tonnage that moves through lock j. All the variables z_k take on values $0 \leq z_k \leq 1$, since they represent fractions of the specified total tonnages.

The network topology of the waterway system is represented in the model by an M by L incidence matrix (a_{ij}), with $a_{ij} = 1$ if movement i would pass through lock j in transitting the system and $a_{ij} = 0$ otherwise. From the definitions of z_k, w_i, D_j, and a_{ij},

$$D_j z_j = \sum_{i=1}^{M} a_{ij} w_i z_{L+i} \quad . \qquad (2\text{-}1)$$

Moving the tonnage $D_j z_j$ through lock j incurs a delay cost $d_j = f_j(z_j)$ (measured in hours/kiloton), where the form of the lock delay function f_j depends partly on D_j. This cost is assumed to be incurred by each movement which passes through lock j. The delays d_j are nondecreasing functions f_j of

the lock load factors z_j, each f_j representing the characteristics of its corresponding lock. The model presently used for the lock delay functions is derived from Goicoechea, et al. [1]:

$$f_j(z_j) = \frac{N_j z_j}{1 - z_j}, \qquad (2\text{-}2)$$

where N_j is the delay cost for lock j at half capacity, when $z_j = \frac{1}{2}$.

The functions (2-2) are asymptotic, increasing without bound as z_j approaches unity. to avoid computational difficulties (e. g., division by zero), the z_j variables are forced to lie within safe bounds as shown below.

2.1 THE NONLINEAR PROGRAM

Let s_i be the gross rate savings (GRS, hours/kiloton) brought about by shipping a kiloton of commodity i via the waterway system as opposed to an alternative mode. Let z be a column vector made up of the variables z_k ($k = 1, \ldots, n$). Taking into account the delay cost at each lock through which each commodity i passes, the net rate savings over the system are a function of z,

$$f(z) = \sum_{i=1}^{M} w_i z_{L+i}(s_i - \sum_{j=1}^{L} a_{ij} d_j) , \qquad (2\text{-}3)$$

where $d_j = f_j(z_j)$.

Each commodity has a net saving factor, measured in hours/kiloton, of

$$(s_i - \sum_{j=1}^{L} a_{ij} d_j) \quad . \qquad (2\text{-}4)$$

The nonlinear programming model for maximizing f subject to the given

constraints on the variables z_k is as follows:

$$\text{maximize} \quad f(z)$$

$$\text{subject to} \quad -D_j z_j + \sum_{i=1}^{M} a_{ij} w_i z_{L+i} = 0 \qquad (j = 1, \ldots, L) \qquad (2\text{-}5)$$

$$G \leq z_j \leq 1 - G \qquad (j = 1, \ldots, L)$$

$$\text{and} \quad 0 \leq z_{L+i} \leq 1 \qquad (i = 1, \ldots, M) \quad .$$

$$i=1$$

$$(j = 1, \ldots, L) \qquad (2\text{-}5)$$

$$G \leq z_j \leq 1 - G \qquad (j = 1, \ldots, L)$$

and $$0 \leq z_{L+i} \leq 1 \qquad (i = 1, \ldots, M) \quad .$$

The constant $G>0$ is a small adjustment to the (0,1) bounds to avoid singularities in the functions f_j, for example, if one of the lock load variables z_j approaches unity.

The nonlinear programming solution method does not depend on a particular form for the lock delay functions f_j. However, the properties of a solution are intimately related to the assumed overall form for the NRS function, f. A much simpler form than (2-3) was used in the preliminary analysis of Goicoechea, et al. [1]. Analysis of this simplified form showed that the number of truly nonlinear degrees of freedom in the model is equal to the number of locks, L, and not the number of movements, M. A similar conclusion was later found to hold for the full model (2-3). The MINOS nonlinear programming package provides options to take advantage of this fact and obtain very efficient solutions for the full model. The fact that there are relatively few nonlinear degrees of freedom also increases the probability that there will be multiple optima.

Note that in the nonlinear program (2-5), the sums (2-1) are incorporated as constraint equations which the variables z_j and z_{L+i} must satisfy at an optimum. It might seem natural to ask why the expressions (2-1) were not simply used to substitute for the lock load variables z_j, thereby decreasing the number of variables. The reasons for incorporating the expressions directly in the nonlinear program will be explained in Section 4.1.

2.2 THE HESSIAN MATRIX

The hessian matrix of second derivatives of the NRS function, f, contains important information about the structure of the optimization problem. In

particular, it shows that the nonlinear program (2-5) actually has a great deal of linearity; it differs from a linear program only in a relatively small subset of L out of the total $n = L + M$ degrees of freedom. As mentioned before, this information can be used to advantage.

The partial derivatives of f with respect to the lock load variables z_j and movement variables z_{L+i} are

$$\frac{\partial f}{\partial z_j} = - \sum_{j=1}^{M} w_i z_{L+i} a_{ij} f_j'(z_j) \quad , \tag{2-6}$$

$$\frac{\partial f}{\partial z_{L+i}} = w_i (s_i - \sum_{j=1}^{L} a_{ij} f_j(z_j)) \quad , \tag{2-7}$$

$$\frac{\partial^2 f}{\partial z_j^2} = - \sum_{j=1}^{M} w_i z_{L+i} a_{ij} f_j''(z_j) \quad , \tag{2-8}$$

$$\frac{\partial^2 f}{\partial z_{L+i}^2} = 0 \quad , \tag{2-9}$$

$$\frac{\partial^2 f}{\partial z_j \, \partial z_{L+i}} = - w_i a_{ij} f_j'(z_j) \quad , \tag{2-10}$$

$$\frac{\partial^2 f}{\partial z_j \, \partial z_{j'}} = 0 \quad , \qquad (2\text{-}11)$$

$$\frac{\partial^2 f}{\partial z_{L+i} \, \partial z_{L+i'}} = 0 \quad . \qquad (2\text{-}12)$$

Here i and i' and j and j' represent differing indices for the movement and lock load variables, respectively ($i \neq i'$, $j \neq j'$). Arranging the second partial derivatives (2-8) - (2-12) in the order of the lock load and movement variables yields the Hessian matrix G illustrated schematically in Figure 1. The shaded areas represent elements which may be nonzero, and the remainder of G has zero entries. The upper left L by L block of G is a diagonal matrix of derivatives (2-8), and the M by L nonzero block and its L by M transpose, both of whose entries are the mixed partial derivatives (2-10), are rank L matrices (L being smaller than M). The full Hessian matrix, G, has at most 2L nonzero eigenvalues.

The number of nonzero eigenvalues of G is equal to the number of directions of nonzero curvature of the function f at any point z in the n-dimensional space of the lock load and movement variables z_k ($k = 1, \ldots, n$). Since f has at least $n - 2L = M - L$ directions of zero curvature at any point, and M is usually much greater than L, the local behavior of f (e.g., at an optimum z^*) is determined largely by local linear effects.

One important implication of there being very few directions of nonzero curvature is that there are correspondingly few nonlinear degrees of freedom in the optimization problem which is to be solved. Generally, an optimization process occurring in a lower-dimensional space is much faster. An iterative method which applies this fact can greatly increase the speed of the solution process.

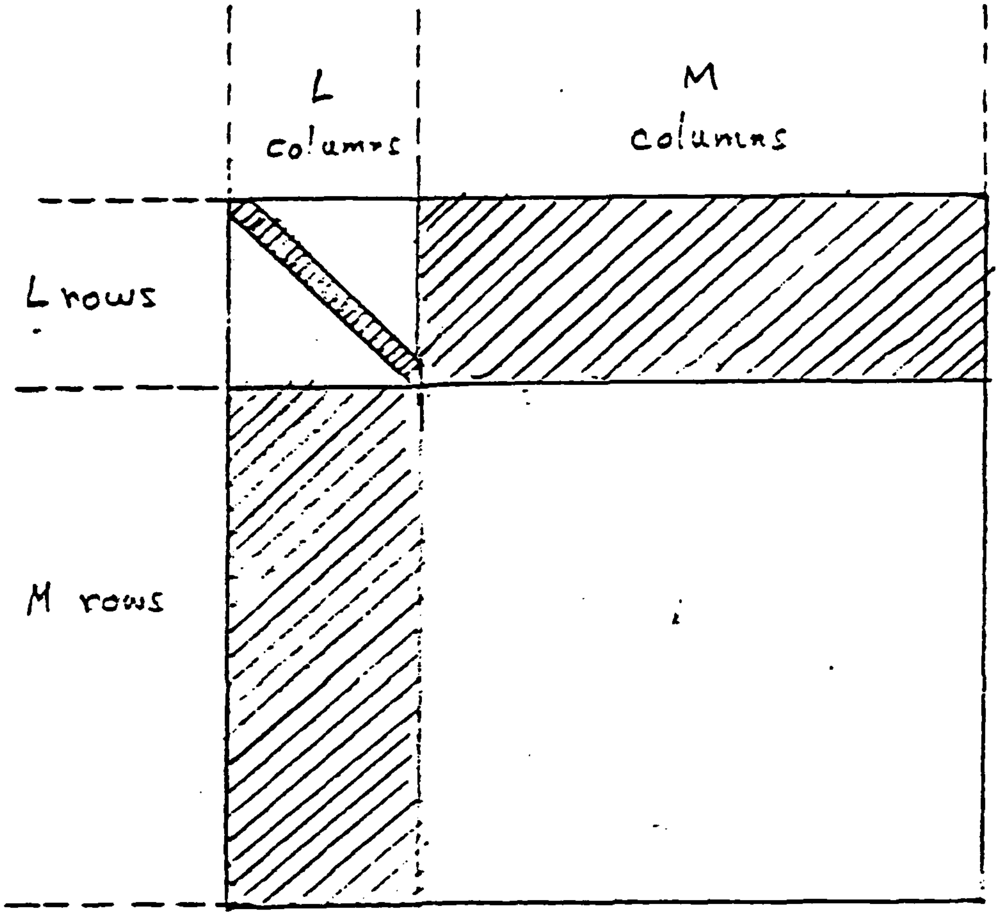

Figure 1. The Hessian Matrix.

Of even greater importance is the degree to which the optimization problem (2-5) resembles a linear program. At any iterative search point in n-dimensional space, the optimization algorithm used will encounter nonlinear effects only in a very low-dimensional subspace. A nonlinear programming package which incorporates the many features of large-scale linear programming packages can use this to great advantage.

3. The Mathematical Model to Identify the Systemic Equilibrium

An examination of the Lagrangian expression of the model above, along with the attendant first order conditions for an optimum suggest that a slight reformulation of f(z) will identify the systemic equilibrium levels of Z_{L+i}, i+1, ..., M. The lagrangian $\Phi(z)$ may be written:

$$\Phi(z) = f(z) + \sum_{k=1}^{L+M} \lambda_k z_k + \sum_{k=1}^{L+M} B_k(1-z_k) + \sum_{j=1}^{L} \alpha_j \left(D_j z_j - \sum_{i=1}^{M} a_{ij} w_j z_{L+i}\right) \quad (3\text{-}1)$$

and the first order conditions for a quasi-saddle point may be written:

$$\frac{\partial \Phi(z)}{\partial z_k} = 0, \quad (k=1,\ldots,L,L+1,\ldots,L+M), \qquad (3\text{-}2)$$

$$\lambda_{kk} z_k = 0, \qquad \lambda_k \geq 0, \qquad (3\text{-}3)$$

$$B_k(1-Z_k) = 0, \quad B_k \geq 0, \text{ and} \qquad (3\text{-}4)$$

$$D_j Z_j = \sum_{L=1}^{M} a_{ij} w_i z_{L+i}, \quad (J = 1, \ldots, L). \qquad (3\text{-}5)$$

Assuming $0 < z_j < 1$ (that there is at least some movement through each lock and no lock operates at 100 percent utilization) gives $\lambda_j = B_j = 0$, $j = 1, \ldots, L$. Equations ((3-2) are then

$$\frac{\partial \Phi(z)}{\partial z_j} = -\sum_{i=1}^{M} w_i z_{L+i} a_{ij} d_j'(z_j) + \alpha_j D_j = 0 \quad (j=1,\ldots,L) \tag{3-6}$$

$$\frac{\partial \Phi(z)}{\partial z_{L+i}} = w_i \left(s_i - \sum_{j=1}^{L} a_{ij} d_j(z_j)\right) + \lambda_{L+i} - B_{L+i} - \sum_{j=1}^{L} a_{ij} w_i \alpha_j = 0 \quad (I=1,\ldots,M) \tag{3-7}$$

Solving (3-6) for α_j using equations (3-5) yields $\alpha_j = z_j d_j'(z_j)$.

Substituting into (3-7) yields $w_i \left(s_i - \sum_{j=1}^{L} a_{ij}(d_j(z_j) + z_j d_j'(z_j))\right) + \lambda_{L+i} - B_{L+1} = 0$

so that $\left(s_i - \sum_{j=1}^{L} a_{ij}(d_j(z_j) + z_j d'(z_j))\right) > 0$ implies $\lambda_{L+1} - B_{L+1} < 0$,

which in turn implies $B_{L+1} > 0$ and $z_{L+1} = 1$. Similarly,

$\left(s_i - \sum_{j=1}^{L} a_{ij} (d_j(z_j) + z_j d'(z_j))\right) < 0$ implies $\lambda_{L+i} - B_{L+i} > 0$, which

implies $\lambda_{L+i} > 0$ and $z_{L+i} = 0$.

Further, $(s_i - \sum_{j=1}^{L} a_{ij} (d_j(z_j) + z_j d'(z_j))) = 0$ implies $\lambda_{L+i} - B_{L+i} = 0$

which implies $\lambda_{L+i} = B_{L+i} = 0$ and $0 < z_{L+i} < 1$. Hence, a movement will

transit the system if and only if $(s_i - \sum_{j=1}^{L} a_{ij}(d_j(z_j) + z_j d'(\ j)))\geq 0$ (3-8)

Now, the equilibrium conditions in SWEENEY [2] are similar in form. They may be expressed as follows:

A movement will transit the system if and only if $(s_i - \sum_{j=1}^{L} a_{ij}\ d_j(z_j)) \geq 0.$

Hence, reformulating $f(z)$ in (2-3) above as $f(z) = \sum_{L=1}^{M} w_i z_{L+i} (s_i - \sum_{j=1}^{L} a_{ij} h_j(z_j))$

where $h_j(z_j) + z_j h'(z_j) = \int d_j(z_j)$ $(j = 1, \ldots, L)$ (3-9) and solving the nonlinear optimization will yield the systemic equilibrium as a solution. Relationship (3-9) is a linear, first-order, exact differential equation whose solution is $h_j(z_j) = d_j(z_j)\ dz_j/z_j$. Hence, so long as $d_j(z_j)$ is integrable, maximizing the function.

$$f(z) = \sum_{L=1}^{M} W_i\ z_{L+i}\ (s_i - \sum_{j=1}^{L} a_{ij}\ h_j(z_j)) \qquad (3\text{-}10)$$

where $h_j(z_j) - \int d_j(z_j) dz_j / z_j$, subject to the same constraints previously described (2-5) will yield as its solution the systemic equilibrium conditions of the navigation system.

4.0 SOLUTION METHOD

Waterways transportation networks can have values for M, the number of movements in the formulation (2-5), in excess of 4000. Values for L can be on the order of 200, for a total of $n = L + M$ in excess of 4200 variables. The mathematical software technology for obtaining efficient and reliable solutions to nonlinear programming problems of this magnitude is relatively recent. The nonlinear programming solution method for both the social and equilibrium models is an application of Stanford University's MINOS software package for large-scale optimization. MINOS applies quasi-Newton minimization methods, reduced-gradient constraint-handling methods, sparse matrix techniques for large-scale problems, and basis strategies derived from linear programming. The input/output capabilities in the package are similar to those of commercial linear programming systems.

The following sections contain a brief overview of how the methods implemented in MINOS are used to achieve maximum efficiency in solving waterways transportation problems. A more comprehensive discussion of the methods is contained in Murtagh and Saunders [3] or [4], which show how MINOS solves more general nonlinear programming problems. The software usage details are contained in Murtagh and Saunders [5] and [6].

4.1 FORMULATING THE CONSTRAINTS

Movement tonnage and lock load fractions z_{L+i} $(i = 1, \ldots, M)$ and z_j $(j = 1, \ldots, L)$ are found which maximize the particular function, either (2-3) or (3-10), subject to the simple bounds and the constraint equations relating lock loads to movements in (2-5). To provide for the event that an iteration point $\mathbf{z}$ has a z_j value close to a bound, the (0,1) bounds for the lock loads are modified by adding a small increment $\pm\epsilon$, to provide bounds $(0 + \epsilon, 1 - \epsilon)$ as shown in (2-5). This avoids computational difficulties inherent in the functions f_j of (2-3) and h_j of (3-10) at the (0,1) bounds.

A brief discussion is in order to explain why the expressions (2-1) were not simply used to substitute for the lock load variables z_j, thereby decreasing

the number of independent problem variables in (2-5). Instead, the expressions are incorporated as constraint equations which the variables z_j and z_{L+i} must satisfy at an optimum. There are two reasons for this, both computational.

First, the asymptotic form of the lock delay functions f_j (2-2) in (2-3), and the h_j of (3-10) as well, cause computational difficulties (e. g., division by zero) when a z_j value approaches 0 or 1. Although this is unlikely to occur at an optimum (for then lock j would be operating near its capacity, causing very expensive delays), it could occur momentarily during the iterative search performed by the nonlinear programming algorithm. There are numerous ways to avoid this problem, the most effective of which involves specifying the lock loads as independent variables. These are readily controlled by specifying lower/upper bounds on them as mentioned above. The equations in (2-5) constrain the z_j values to represent the lock loads.

The equality-constrained model also yields a substantial efficiency improvement. In substituting for the lock loads $D_j z_j$ as dependent variables, the partial derivatives of f with respect to its independent variables, i. e., the movement variables, are expensive to compute. However, the reduced gradient method of MINOS handles linear constraints such as those in (2-5) very efficiently. In particular, the added z_j variables are immediately put into a basic set, as in linear programming, and do not really increase the problem size. Moreover, the derivatives of f with respect to lock load variables and movement variables can be computed in a fraction of the computer time required by the substitution approach. Since $f(z)$ and the partial derivatives in the gradient vector $g(z)$ may have to be computed many times during the iterative search process to find an optimum, the equality-constrained model is a great deal more efficient. An order-of-magnitude computer cost reduction was demonstrated on a sample data case with $L = 2$ locks and $M = 184$ movements. On a larger case, the cost reduction would be greater.

4.2 THE REDUCED GRADIENT METHOD

Let A be the L by $n = L + M$ matrix of coefficients for the linear equations (2-1) incorporated in (2-5). The first L columns of A form a diagonal matrix of entries $-D_j$ for the first L variables z_j in the solution vector z. The

remaining M columns form an L by M matrix of coefficients a_{ijw_i} ($j = 1, \ldots, L$; $i = 1, \ldots, M$) for the remaining M variables z_{L+i} in z.

Then (2-5) can be written in vector/matrix form as

$$\begin{aligned} &\text{minimize} && -f(z) \\ &\text{subject to} && A\,z = 0 \qquad\qquad (4\text{-}1) \\ &\text{and} && 0^{+} \le z \le 1^{-}, \end{aligned}$$

where the first L components of the vectors 0^{+} and 1^{-} are δ and $1 - \delta$ and the remaining M components are 0 and 1, respectively, corresponding to the bounds on the variables z_j and z_{L+i} in (2-5). The minimization of -f is actually performed by MINOS to solve the equivalent problem of maximizing f, a standard practice in modern optimization techniques.

Each major iteration of a reduced gradient method consists of solving the L by n system of equations $A\,z = 0$ to eliminate L of the variables z_k in terms of the remaining n - L variables. Thus, L of the variables (as it turns out, the lock load variables z_j) are eliminated from the independent set and become dependent, or <u>basic,</u> variables. The remaining variables in z are assigned to either a <u>non-basic</u> or a <u>superbasic</u> set throughout the iteration. The non-basic variables are held fixed at their lower or upper bounds, and the superbasic variables are varied by a fast-converging gradient method to minimize the function -f restricted to the reduced subspace of basic and superbasic variables. At the end of the iteration, a constrained stationary point has been reached and MINOS examines the Lagrange multipliers (reduced costs) for the non-basic variables to determine whether this is an optimum, much in the manner of the linear programming simplex method. If -f can be further minimized by allowing one or more of the non-basic variables to become superbasic, or if a basic variable has reached one of its bounds, the appropriate changes are made to the three sets of variables and a new reduced gradient iteration begins.

A brief presentation is given to make these ideas more precise. The references

given at the beginning of this chapter should be consulted for a good description. For the current reduced gradient iteration, let the constraint matrix A be partitioned into an L by L basis B, along with the L by n_s matrix N corresponding to the superbasic and non-basic variables, respectively. From the form of the constraints in (2-5), a nonsingular L by L basis matrix B can always be found so that

$$A = [B \quad S \quad N] \quad , \qquad (4\text{-}2)$$

and the constraints in (4-1) can be written

$$\begin{bmatrix} B & S & N \\ 0 & 0 & I \end{bmatrix} \begin{bmatrix} z_B \\ z_S \\ z_N \end{bmatrix} = \begin{matrix} 0 \\ \\ b_N^+ \end{matrix} \quad , \qquad (4\text{-}3)$$

where the 0's in the left-hand side matrix are zero matrices of appropriate size and I is the $(n - L - n_S)$ by $(n - L - n_S)$ by $(n - L - n_S)$ identity matrix. The **0** on the right is an L-dimensional vector of 0's, b_N^+ represents the appropriate fixed bound values for the non-basic variables in the vector z_N, and z is partitioned into the basic, superbasic and non-basic sts z_B, z_S, and z_N.

Let the gradient vector g(z) of − f evaluated at a point z be denoted simply as g, and let g be partitioned in a manner corresponding to z. The first-order necessary conditions for an optimum in (4-1) specify that the equations (4-3) hold and that

$$\begin{bmatrix} B^T & 0 \\ S^T & 0 \\ N^T & I \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} g_B \\ g_S \\ g_N \end{bmatrix} \quad , \qquad (4\text{-}4)$$

where α and β are appropriate vectors of Lagrange multipliers, corresponding, respectively, to the equality constraints and to the non-basics at their bounds.

If a solution has not yet been reached, the current subspace optimum corresponding to (4-4) will be a constrained stationary point, but some of the multipliers β_i will have the wrong signs. A subset of the corresponding nonbasic variables $z_{N,i}$ will be moved into the superbasic set for the next subspace optimization using the superbasic variables. This is often referred to as a pricing operation on the nonbasic variables.

Following each pricing operation, a sequence of nonlinear minimization iterations is performed to reach a new constrained stationary point. Only the superbasic variables in z_S need be varied to do this. The size of the superbasic set is controlled by the user via the the SUPERBASICS option in the SPECS input data st, which provides overall problem specifications to MINOS. The user can also control the maximum size of the subset of non-basic variables to be released from their bounds and made superbasic by specifying a value with the MULTIPLE PRICE option. This is how the problem structure incorporated in the Hessian matrix $G(z)$ of $-f$ is used to advantage: These input options are set to a value roughly equal to the number of nonlinear degrees of freedom in the problem. This allows MINOS the freedom to put into the nonlinear minimization process a number of variables roughly equal to the number of nonlinear effects, while limiting the total size of the superbasic set for faster subspace solutions.

4.3 THE QUASI-NEWTON METHOD

By incorporating the multipliers α and β into a column vector ,

$$\lambda = \begin{bmatrix} \alpha \\ \beta \end{bmatrix} , \qquad (4\text{-}5)$$

the optimality conditions (4-3) and (4-4) can be written more compactly as

$$A^T \lambda = 0$$

$$A z = 0 \qquad (4\text{-}6)$$

$$z_N = b_N^+$$

for an optimum z with optimal multiplier values , and with the non-basic parition z_N of z fixed at the optimum bounds b_N^+.

The L constraint equations and $n - L - n_S$ bound assignments in (4-6) define a subspace of dimension $n - (L + (n - L - n_S)) = n_S$, the number of superbasic variables identified in the last pricing operation. The rows of A and the unit vectors corresponding to the bounds are normal to this subspace. Let Z be an n by n_S matrix whose columns form a basis for this subspace. The Z actually used is

$$Z = \begin{bmatrix} -B^{-1}S \\ I \\ 0 \end{bmatrix}$$

Since the rows of A are normal to Z,

$$A Z = 0 \quad , \qquad (4\text{-}7)$$

hence, nonlinear iteration steps restricted to the subspace will satisfy the equality constraints an currently active bounds. All that is required is to

monitor the closeness of the basic and superbasic variables to their bounds.

The optimality conditions for an unconstrained minimum of $-f$ over the subspace are that the reduced gradient of $-f$ be zero and that its reduced Hessian show non-negative curvature, i. e.,

$$Z^T g = 0 \qquad (4\text{-}8)$$

and

$$v^T (Z^T G Z) v \geq 0 \qquad (4\text{-}9)$$

for all n_S-vectors v. The n_S-vector $Z^T g$, the reduced gradient, is a projection of the gradient g into the subspace of superbasics and $Z^T GZ$, the reduced Hessian, is a projection of the Hessian G.

The nonlinear minimization method of MINOS is an iterative method which solves (4-8) for the current set of superbasics following each pricing operation. The method applies the Newton iteration

$$(Z^T G Z) p_S = -Z^T g \qquad (4\text{-}10)$$

The iterative step-vector p_S is scaled down in length to insure that bounds on the basic and superbasic variables are not violated and that the resulting step

$$z+ = z + Zp_S \qquad (4\text{-}11)$$

results in a decrease in $-f$, i. e., $-f(z^+) < -f(z)$. The method actually uses a quasi-Newton approximation to $Z^T G Z$ (see Murtagh and Saunders [3] or [4]), which avoids having to compute second derivatives and causes the iteration process to be numerically stable.

4.4 NOTES ON THE SOLUTION

The functions f for the social and equilibrium models take on values many

orders of magnitude higher than the order of unity magnitudes of the z_k variables. To further aid numerical stability in the quasi-Newton search process, the functions are scaled by an appropriate constant.

Once a solution has been found for the current data case, MINOS provides an additional call to the CALCFG subroutine which calculates the f(z) and g(z) values at any point z requested by MINOS. During this final call, the unscaled NRS function and gradient for the social model are calculated, regardless of whether a social or equilibrium optimum has just been found. This allows the correct reporting of system benefits and their margins at the optimum. The reported gradient will be correct, however, the reduced gradient will be erroneous due to the rescaling and should be ignored.

5.0 COMPUTER USAGE DETAILS

Murtagh and Saunders [5] and [6] give detailed descriptions of the usage of MINOS in solving nonlinear programming problems. Briefly, MINOS is a Fortran package and requires a user-coded Fortran "function box" subroutine, named CALCFG, to calculate the function values f(z) and gradient vectors g(z) at iteration points z specified by MINOS. It also requires three input data sets, which may reside on a single logical file. A particular application, e. g., the waterways optimization models described in this paper, usually requires a matrix generator program. A matrix generator is written especially for the application, to convert raw problem input data to the format of these three data sets. This section describes the usage of MINOS with the CALCFG subroutine and matrix generator for waterways transportation problems.

5.1 EXECUTING MINOS

Figure 2 shows the overall flow for executing one or more data cases for a single waterways scenario. MINOS is called from a main program which reserves the storage required by MINOS, sets the unit number for the system input stream for transmission to subroutine CALCFG, initializes the data case counter, and calls a MINOS package subroutine, GO, which in turn calls the subroutine MINOS. The GO subroutine calls MINOS in a loop to execute all the data cases stacked on the MINOS input file (system default input stream, usually unit 5). The

large storage array in the main program can be increased in size if more storage is required by MINOS to handle large data cases.

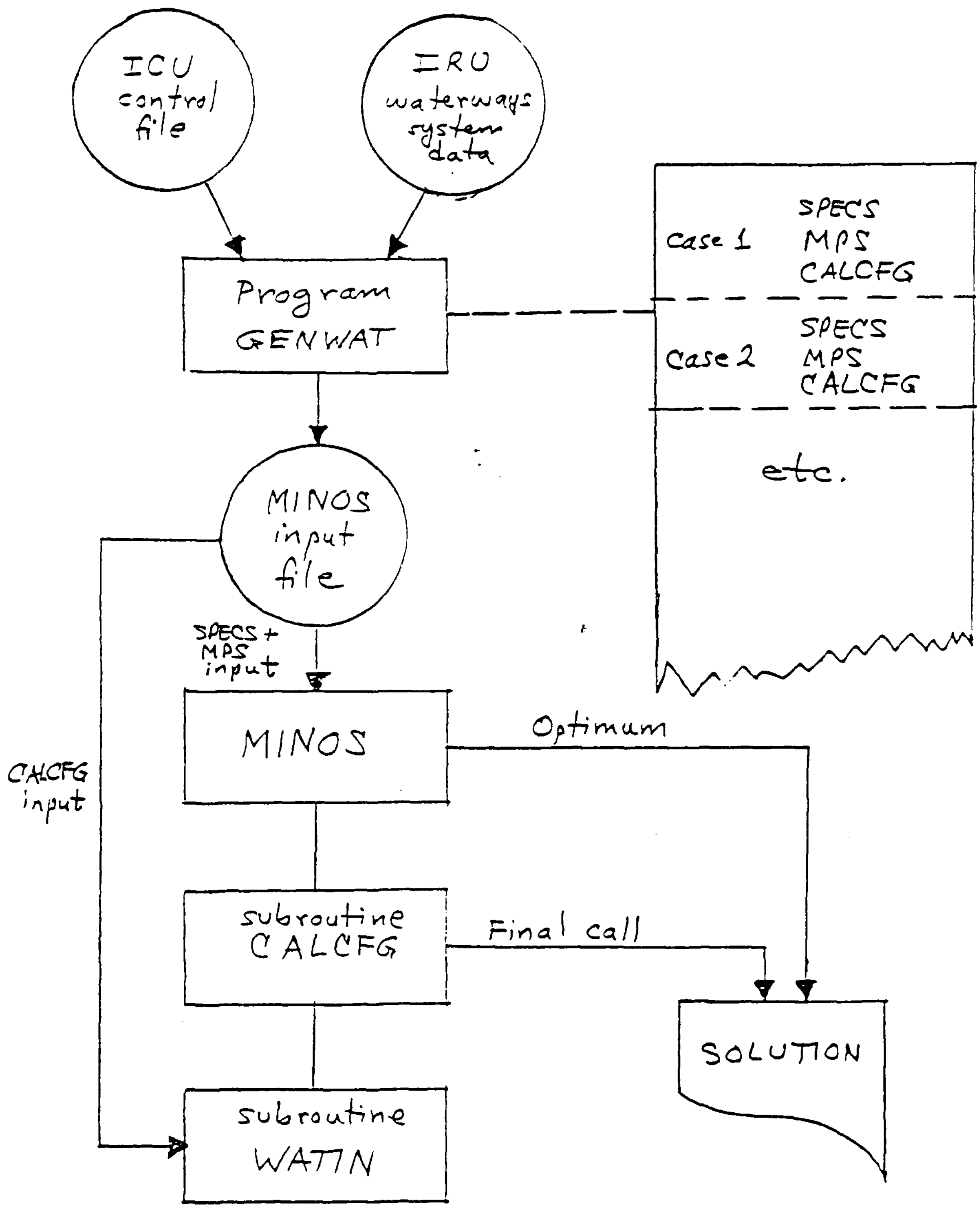

Figure 2. Overall Flow

The subroutine CALCFG is called from MINOS repeatedly during the iterative solution process for one data case. Each time MINOS calls CALCFG, it provides the latest iterative estimate of the optimal solution values in the vector z. CALCFG calculates the function value f(z) and partial derivatives in the gradient vector g(z) and returns these to MINOS. During the first function call from MINOS, however, CALCFG calls a subroutine, WATIN, which reads data required for the calculations in CALCFG. This data makes up the CALCGF data set, one of the three MINOS input data sets referred to earlier. The data includes the lock function coefficients, GRS values, movement tonnages (in kilotons), and waterway network incidence matrix for the case being run. If several cases are being run in one execution run of MINOS, subroutine WATIN assumes that all cases following the first have the same overall waterways scenario. They only differ in the amount of tonnage w_i for each of the movement quantities, since they represent different years for which movement tonnage projections have been made. Hence, for the subsequent cases WATIN reads only the new tonnages.

The three data sets used by MINOS are called SPECS, CALCFG, and MPS. The purpose of the CALCFG data set has just been given. The SPECS data set (which contains only about 16 lines) consists of key words and numerical values in a free field format. It describes the major aspects of the current data case to MINOS (number of variables, etc.) and specifies the mode in which MINOS is to run. For example, the MULTIPLE PRICE and SUPERBASICS options are specified as described in Section 4.2. The MPS data set is the largest by far; it lists the nonzero coefficients of the variables in each constraint row, keyed by variable (column) and row name. It also specifies which movement variables are to be initially set to their upper bound values (e. g., via the input line 'UP INITIAL MOVM192') to accelerate the convergence of MINOS.

5.2 THE MATRIX GENERATOR

The matrix generator, Fortran program GENWAT, reads the raw data and produces one or two MINOS input files containing the three data sets described above. If two files are produced, one file contains the MPS data set, and the other contains the SPECS and CALCFG data sets. The SPECS/CALCFG file must always be given the system default input stream unit number. However, for a multi-case

run (several years of data to be analyzed), only one file is produced.

The following discussion is oriented toward production of a single MINOS input file. For a multi-case run, the three data sets are repeated for each data case in the order SPECS-MPS-CALCFG. Execution of MINOS stops when an end-of-file has been read.

The comments in the GENWAT Fortran source code describe the matrix generation process and show how to accommodate larger data cases by changing array dimensions. They also show how to set the output file unit numbers to produce either one or two files, as described above. It is recommended that the single file option always be used.

GENWAT accepts raw data from two files, whose unit numbers have the Fortran variable names ICU and IRU (the values used are set in a data statement). File ICU controls the reading of the waterways system/movement data on file IRU. The first record of ICU specifies the format for reading the multi-year movement data and subsequent records provide the numbers corresponding to the particular years of movement data to be run. The organization of file ICU is shown in Table 1. The movement and waterways scenario data are on file IRU, organized as shown in Table 2.

Table 1. THE CONTROL FILE ICU.

Input Line	Variables Read	Format
1	(MAT(I),I = 1,20)	(20A4)
2	IYEAR	(110)
	•	•
	•	•
	•	•
LAST RECORD	IYEAR	
-1		
LAST RECORD	Value 0 or NYEARS	(110)

Table 2. THE WATERWAYS DATA FILE IRU.

Input Line	Variables Read	Format
1	MOVEMS LOCKS NYEARS	(2I4,I3)
2	ANUM(1) DENOM(1)	(F5.3,F7.0)
	.	.
	.	.
	.	.
LOCKS+1	ANUM(LOCKS) DENOM(LOCKS)	.
LOCKS+2	(TEMP(I),I=1,NYEARS), (IA(K),K=1,LOCKS),GRS(1) (possibly more than one line for each such record)	(format on file ICU)
	.	.
	.	.
	.	.
LOCKS+MOVEMS + 1	(TEMP(I),I=1,NYEARS), (IA(K),K=1,LOCKS),GRS(MOVEMS)	.

Each record of file ICU following the first specifies, for each data case, which year is to be read form the multi-year movement tonnage projections on the data lines numbered LOCKS+2 through LOCKS+MOVEMS+1 on file IRU. Here, LOCKS is the number L of locks in the waterway network and MOVEMS is the number M of movements. Their values are read on line 1, along with the total number of years of data, NYEARS, for each movement. Input lines 2 through LOCKS+1 contain the coefficients of the asymptotic lock functions f_j of (2-3) or h_j of (3-16). ANUM(J) is the value N_j in (2-3) and DENOM(J) is the capacity D_j of lock j in kilotons.

Finally, the movement data on file IRU is read using the variable format in the first record of ICU. The temporary storage array TEMP in GENWAT contains the tonnage projections for the current movement for all years. The value of IYEAR read from ICU is used to select the proper value, TEMP(IYEAR), for use in the current data case. The INTEGER array IA contains the incidence matrix values corresponding to the current movement and all locks, i. e., IA(K) equals 1 if the current movement would pass through lock K, 0 if not. The REAL value GRS(L) is the gross rate savings value s_ℓ for movement .

Program GENWAT reads one additional file, whose unit number is denoted LAIA in the Fortran source code. This file supplies left-adjusted integers for use in creating the names of the columns (variables) and rows (constraints) in the MPS data set. The LAIA file was created by a simple Fortran program which wrote out 5000 lines, consisting of the integers 1 through 5000, left-adjusted. When read in A4 format by Program GENWAT, these integers can be concatenated to a four-character hollerith literal prefix to form eight-character names. For example, movement variable 192 is given the name MOVM192 by GENWAT. This name is created by GENWAT from the stored prefix MOVM (for movement) and the hollerith literal 192b (b for blank) read from file LAIA. Similarly, lock load variables have the prefix LOAD (e. g., LOAD15) and the constraint row names have the prefix LOCK (e. g., LOCK 15).

The output on unit IPU (IPU is normally set to 6, the usual system default output stream) contains any diagnostics issued by Program GENWAT. If there are none, the output file ISPEC, containing the SPECS, MPS, and CALCFG data, should be ready for input to MINOS. Sample control statement sequences for running

both programs GENWAT and WATERW (the program which calls MINOS) are included with this report, in the form of dayfiles from actual runs on the BCS EKS-MAINSTREAM system. In the sample runs, Program GENWAT was run on a Cyber computer and MINOS was run on a Cray.

6. EXTENSIONS OF THE MODELS

The versitility of the models presented in Sections 2 and 3 above in conjunction with the MINOS solùtion algorithim makes possible the incorporation of more robust assumptions directly into the models themselves. For example, when different potential commodity movements have different costs per ton per hour of delay at the different system locks equation (2-3) may now be expressed as:

$$f(Z) - \sum_{L=1}^{M} w_i Z_{L+i} \left(s_i - \sum_{J=1}^{L} c_{ij} d_j(Z_j) \right) \qquad (6\text{-}1)$$

where s_i is now the GRS measured in dollars per ton and c_{ij} is the per ton per hour cost of delay in dollars for movement i at lock j ($c_{ij} = 0$ if $a_{ij} = 0$). Hence, maximizing f(Z) subject to the constraints in (2-5) will determine the economical optimal level of system usage. further, following a similar course of logic as that used in Section 3, it can be demonstrated that maximizing the function

$$f(Z) = \sum_{i+1}^{M} w_i Z_{L+i} \left(s_i - \sum_{J=1}^{L} c_{ij}\, h_j(Z_j) \right) \qquad (6\text{-}2)$$

where $$h_j(Z_j) = e^{-K_j Z_j} K_j \int e^{K_j Z_j} d_j(Z_j)\, dZ_j \quad (j=1,\dots,L) \qquad (6\text{-}3)$$

with $$K_j = \frac{\sum_{L=1}^{M} (c_{ij})\, D_j}{\left(\sum_{i=1}^{M} a_{ij} \right) \left(\sum_{L=1}^{M} w_i Z_{L+i}\, c_{ij} \right)} \qquad (6\text{-}4)$$

subject to the constraints in (2-5) will yeild the system equilibrium levels of system usage with the varying delay costs incorporated by the differing c_{ij}.

The incorporation of this change to the modeling makes no difference to the MINOS solution algorithim. The formulation has exactly the same mathematical structure as the formulations in Sections 2 and 3 above. Consequently, the MINOS algorithim can be used to find the equilibrium levels of system usage board on average ???? delay costs per ton varying over different movements and locks.

Similarly, potential commodity movements with back-hauls may be directly incorporated into the model formulation. This may be accomplished by making the delay functions at each lock a function of the weighted summation of individual movement tonnages by rewriting equations (2-5) as

$$D_j' Z_j = \sum_{i=1}^{M} a_{ij} k_{ij} w_{ij} Z_{L+i} \quad (j=1, \ldots, L). \qquad (6\text{-}5)$$

where $k_{ij} = 1$ if movement i has a back-haul and $k_{ij} = 2$ if movement i has no backhaul. Once again, this reformulation is mathematically identical to those in Sections 2 and 3 above, and the MINOS algorithim can be used to find solutions for the equilibrium levels of system usage based on average or marginal delay costs.

7. CONCLUSIIONS

This paper has presented a nonlinear programming tool for investigating the economics of inland waterway transportation systems. The model presented explicitly incorporates the interaction of system components into the economic analysis of that system. The model is robust in that it may be used to compute the economic benefits of a navigation system or alterations to that system under a wide variety of assumptions concerning the operation of the system. The system-wide economic impacts of user charges, congestion fees, and capacity expansion measures are all readily analyzed using this tool. Investment strategies to achieve the greatest economic benefit for a limited capital budget can be determined and analyzed using the model. The model may be used to design congestion fees to better manage an existing navigation system.

APPENDIX A

COMPUTER RESOURCES REQUIRED FOR EXECUTION OF SAMPLE PROBLEM

```
.42.USER,*.  4. J. HEALY/575-5134/9C-01/G-75
.42.43
.42.USER NUMBER=CEW3I5
.42. CHARGE LIMITS OVERRIDDEN
.42.
.43. JOB ENTRY 84/02/02. 10.39.33.
.43. OWNING ST=EKS1        OWNING UN=CEW3I5
.43. ORIGIN ST=EKS1       ORIGIN UN=(LOCAL)
.43. DEST   ST=EKS1       DEST   UN=SC1183
.43.GET,SGWT.
.44.FTN,I=SGWT,B=BGWT,A,T,EL=A,R=3.
.44.#FTN        4.8-564    VER-83334
.50.         .218 CP SECONDS COMPILATION TIME
.50.GET,DICU,DUGLY5,DLAIA.
.59.COPYBF,DICU,OUTPUT.
.59. EOI ENCOUNTERED.
.59.COPYBF,DUGLY5,OUTPUT.
.59. EOI ENCOUNTERED.
.59.REWIND,DICU,DUGLY5.
.59.BGWT,DICU,,,,DLAIA,DMUG2,DUGLY5.
.03.#FCL        LVL-554    VER-83265
.03./PRG USED/GENWAT
.09.      STOP
.09.      042000 MAXIMUM EXECUTION FL.
.09.        1.623 CP SECONDS EXECUTION TIME.
.09.EXIT(U)
.10.REPLACE,DMUG2.
.14.CATLIST,LO=F,FN=DMUG2.
.15. CATLIST COMPLETE.
.15.EXIT(U)
.15.DAYFILE,DFMJH.
.15. USER DAYFILE DUMPED.
.15.REPLACE,DFMJH.
.15.EXIT.
.17.
.17. RUN DATE  84/02/02.  RUT SECS     11.748
.17. UNITS            NUMBER       CCUS    PERCENT
.17. CPU SECS          1.952     33.654     77.564
.17. CMP UNITS         1.051      5.572     12.766
.17. DISK REQS           215      2.313      5.310
.17. DISK SECT          4094      0.551      1.262
.17. JOB INITIATION               1.350      3.093
.17. JOB PROCESSING CCUS         43.645
.17.
```

Matrix Generator run

```
CSP     FE[illegible]=ETAMIH.
CSP     FETCH.DN=DMUG2.DT=C.DS=FF.
CSP     ROUTE.DN=DMUG2.DC=PR.PS.UN=SC1183.MB=MPRT.ND.
USER    DATASET DMUG2   IS NOW JOB   -    DG3QJSR
CSP     REWIND.DN=DMUG2.
CSP     CFT.I=SWT2.CN=A.
USER    CF000 - CFT VERSION -    01/20/84 1.09
USER    CF001 - COMPILE TIME =    0.1350 SECONDS
USER    CF002 -       301 LINES,       182 STATEMENTS
CSP     FETCH.DN=MINOSC.UN=ETAMIH.
CSP     ASSIGN.DN=DMUG2.A=FT05.
CSP     COST.LO=F.
USER
USER     RUN DATE      02/02/84   PRUT SECS        1.485
USER     UNITS           NUMBER        CCUS      PERCENT
USER     CP SECS          0.494      15.955       46.478
USER     CM UNITS         0.017       1.247        3.632
USER     DISK REQS           36       0.083        0.242
USER     DISK BLOCKS        433      17.043       49.647
USER     JOB PROCESSING CCUS         34.328
USER                                                          MINOS
CSP     LDR.LIB=MINOSC.MAP=PART.                               run
USER    LD000 - BEGIN EXECUTION
USER    FT063 -     STOP                    IN WATERW
CSP     COST.LO=F.
USER
USER     RUN DATE      02/02/84   PRUT SECS        6.867
USER     UNITS           NUMBER        CCUS      PERCENT
USER     CP SECS          5.050     163.061       77.429
USER     CM UNITS         0.219      16.128        7.659
USER     DISK REQS           66       0.152        0.072
USER     DISK BLOCKS        794      31.252       14.840
USER     JOB PROCESSING CCUS        210.593


USER
CSP     EXIT(U)
CSP     LOGFILE.L=DFMJH.
CSP     STORE.DN=DFMJH.DT=C.DS=FF.
CSP     REWIND.DN=$OUT.
CSP     COPYD.I=$OUT.O=DNUG22.
USER    FT048 - COPY OF      3239 RECORDS        2 FILES COMPLETED
CSP     STORE.DN=DNUG22.DT=C.DS=FF.
CSP     END OF JOB
USER
USER     RUN DATE      02/02/84   PRUT SECS        7.460
USER     UNITS           NUMBER        CCUS      PERCENT
USER     CP SECS          5.098     164.615       74.201
USER     CM UNITS         0.225      16.534        7.453
USER     DISK REQS           86       0.199        0.090
USER     DISK BLOCKS       1029      40.501       18.256
USER     JOB PROCESSING CCUS        221.849
USER
USER     ITEMS CHARGED SEPARATELY
USER     OUTPUT SECTORS                    464
USER
USER     PRIORITY REQUESTED                  2
```

APPENDIX B

Computer Results for a Sample Problem

The following system descriptors apply:

- o 229 commodity movements
- o 16 locks of equal capacity and average processing time

SYSTEM EQUILIBRIUM

YEAR 1

LOCK	TONNAGE	DELAY
1	25005.0	0.6
2	25005.0	0.6
3	25005.0	0.6
4	24939.0	0.6
5	24799.0	0.6
6	24799.0	0.6
7	24380.0	0.6
8	24380.0	0.6
9	24380.0	0.6
10	24380.0	0.6
11	12542.0	0.2
12	14446.0	0.3
13	15279.0	0.3
14	15274.0	0.3
15	35816.0	1.5
16	33594.0	1.2

ANNUAL TONNAGE 40707

YEAR 2

LOCK	TONNAGE	DELAY
1	28213.9	0.8
2	28213.9	0.8
3	28213.9	0.8
4	28138.9	0.8
5	27988.9	0.8
6	27988.9	0.8
7	27503.9	0.8
8	27503.9	0.8
9	27503.9	0.8
10	27503.9	0.8
11	14511.0	0.3
12	16755.0	0.3
13	17767.0	0.4
14	17761.0	0.4
15	40918.9	2.4
16	38320.9	1.8

ANNUAL TONNAGE 46503.94

SOCIAL OPTIMUM

YEAR 1

LOCK	TONNAGE	DELAY
1	19498.0	0.4
2	19498.0	0.4
3	19498.0	0.4
4	19432.0	0.4
5	19292.0	0.4
6	19292.0	0.4
7	18873.0	0.4
8	18873.0	0.4
9	18873.0	0.4
10	18873.0	0.4
11	12538.0	0.2
12	14442.0	0.3
13	15275.0	0.3
14	15270.0	0.3
15	30305.0	0.9
16	28083.0	0.8

ANNUAL TONNAGE 35196.03

YEAR 2

LOCK	TONNAGE	DELAY
1	20560.5	0.5
2	20560.5	0.5
3	20560.5	0.5
4	20485.5	0.4
5	20335.5	0.4
6	20335.5	0.4
7	19850.5	0.4
8	19850.5	0.4
9	19850.5	0.4
10	19850.5	0.4
11	14506.0	0.3
12	16737.0	0.3
13	17749.0	0.4
14	17743.0	0.4
15	33273.5	1.2
16	30675.5	1.0

ANNUAL TONNAGE 38845.46

SYSTEM EQUILIBRIUM

YEAR 3

1	29445.9	0.9
2	29445.9	0.9
3	29445.9	0.9
4	29340.9	0.9
5	29157.9	0.9
6	29157.9	0.9
7	28470.9	0.8
8	28470.9	0.8
9	28470.9	0.8
10	28470.9	0.8
11	19521.0	0.4
12	22532.0	0.5
13	23990.0	0.6
14	23982.0	0.6
15	46669.9	5.0
16	43198.9	3.0

ANNUAL TONNAGE 54187.93

YEAR 4

1	27159.6	0.7
2	27159.6	0.7
3	27159.6	0.7
4	27024.6	0.7
5	26807.6	0.7
6	26807.6	0.7
7	25888.6	0.7
8	25888.6	0.7
9	25888.6	0.7
10	25888.6	0.7
11	25973.0	0.7
12	29897.0	0.9
13	31962.0	1.1
14	31952.0	1.1
15	50355.6	11.6
16	45727.6	4.3

ANNUAL TONNAGE 60154.57

SOCIAL OPTIMUM

YEAR 3

1	20239.1	0.4
2	20239.1	0.4
3	20239.1	0.4
4	20134.1	0.4
5	19951.1	0.4
6	19951.1	0.4
7	19264.1	0.4
8	19264.1	0.4
9	19264.1	0.4
10	19264.1	0.4
11	19487.0	0.4
12	22471.0	0.5
13	23929.0	0.6
14	23921.0	0.6
15	37432.1	1.7
16	33961.1	1.3

ANNUAL TONNAGE 44935.13

YEAR 4

1	18600.8	0.4
2	18600.8	0.4
3	18600.8	0.4
4	18465.8	0.4
5	18248.8	0.4
6	18248.8	0.4
7	17329.8	0.3
8	17329.8	0.3
9	17329.8	0.3
10	17329.8	0.3
11	25765.0	0.7
12	29672.0	0.9
13	31737.0	1.1
14	31727.0	1.1
15	41605.8	2.5
16	36977.8	1.6

ANNUAL TONNAGE 51387.77

SYSTEM EQUILIBRIUM

YEAR 5

1	23128.5	0.6
2	23128.5	0.6
3	23128.5	0.6
4	22952.5	0.5
5	22689.5	0.5
6	22689.5	0.5
7	21462.5	0.5
8	21462.5	0.5
9	21462.5	0.5
10	21462.5	0.5
11	32181.0	1.1
12	37035.0	1.6
13	39725.0	2.1
14	39714.0	2.1
15	51671.5	20.5
16	45867.5	4.4

ANNUAL TONNAGE 64104.49

YEAR 6

1	23060.9	0.5
2	23060.9	0.5
3	23060.9	0.5
4	22830.9	0.5
5	22515.9	0.5
6	22515.9	0.5
7	20932.9	0.5
8	20932.9	0.5
9	20932.9	0.5
10	20932.9	0.5
11	33371.0	1.2
12	39133.0	2.0
13	42472.0	2.8
14	42459.0	2.8
15	51732.8	21.2
16	44787.8	3.7

ANNUAL TONNAGE 67055.82

SOCIAL OPTIMUM

YEAR 5

1	19437.8	0.4
2	19437.8	0.4
3	19437.8	0.4
4	19261.8	0.4
5	18998.8	0.4
6	18998.8	0.4
7	17771.8	0.4
8	17771.8	0.4
9	17771.8	0.4
10	17771.8	0.4
11	25651.1	0.7
12	30485.1	1.0
13	32961.4	1.2
14	32950.4	1.2
15	41709.7	2.6
16	35905.7	1.5

ANNUAL TONNAGE 53908.96

YEAR 6

1	20750.6	0.5
2	20750.6	0.5
3	20750.6	0.5
4	20520.6	0.5
5	20205.6	0.4
6	20205.6	0.4
7	18622.6	0.4
8	18622.6	0.4
9	18622.6	0.4
10	18622.6	0.4
11	25203.6	0.6
12	30965.6	1.0
13	33996.6	1.3
14	33983.6	1.3
15	41593.2	2.5
16	34648.2	1.3

ANNUAL TONNAGE 56608.21

SYSTEM EQUILIBRIUM

YEAR 7

1	23630.7	0.6
2	23630.7	0.6
3	23630.7	0.6
4	23376.7	0.6
5	23038.7	0.5
6	23038.7	0.5
7	21302.7	0.5
8	21302.7	0.5
9	21302.7	0.5
10	21302.7	0.5
11	32643.0	1.1
12	38777.0	1.9
13	42961.0	3.0
14	42948.0	3.0
15	51733.7	21.2
16	44367.7	3.5

ANNUAL TONNAGE 68314.73

SOCIAL OPTIMUM

YEAR 7

1	20119.6	0.4
2	20119.6	0.4
3	20119.6	0.4
4	19865.6	0.4
5	19527.6	0.4
6	19527.6	0.4
7	17791.6	0.4
8	17791.6	0.4
9	17791.6	0.4
10	17791.6	0.4
11	26046.0	0.7
12	32180.0	1.1
13	36026.0	1.5
14	36013.0	1.5
15	41996.6	2.6
16	34630.6	1.3

ANNUAL TONNAGE 58239.60

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1. Goicechea, A., Sweeney, D., Sharp, F. M., and Burns, J. J. (1983). A Transportation Model for Economic Policy Analysis of National Inland Waterways Navigation, submitted to the 24th Annual Meeting of the Transportation Research Forum, November 3-6, 1983, Washington, D.C.

2. Sweeney, D. (1983). A System Equilibrium Model for Economic Policy Analysis of National Inland Waterways Navigation, Navigation Division, Institute for Water Resources, U.S. Army Corps of Engineers, Ft. Belvoir, Virginia, December, 1983.

3. Murtagh, B.A., Saunders, M.A., Large-Scale Linearly constrained Optimization.

4. Murtagh & Saunders (1983).

5. Murtagh, B. A., Saunders, M. A., MINOS User's Guide, Technical report 77-9, Stanford University, Systems Optimization Laboratory, 1977 (revised 1981).

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PART III

REVIEW COMMENTS

by

OUTSIDE EXPERTS

A Review of Three Papers

Draft of "SYSTEMS EVALUATION"
by Ron Keeney. March, 1984

Draft of "A SYSTEM EQUILIBRIUM MODEL FOR ECONOMIC POLICY
ANALYSIS OF NATIONAL INLAND WATERWAYS NAVIGATION"
by Don Sweeney, December, 1983

Draft of "A NONLINEAR PROGRAMMING MODEL TO MEASURE
ECONOMIC IMPACTS OF INLAND NAVIGATION SYSTEMS"
by Don Sweeney and Michael Healy, February, 1983

Reviewed by Dr. J. Royce Ginn
Cambridge Information International
March, 1984

INTRODUCTION

The three papers being reviewed present three different methods of modelling the movement of goods on a waterway. All three papers are aimed at the determination of the "benefits" derived by these movements, and ultimately at the evaluation of some "project", either a navigational improvement, a construction project, or the imposition of tolls or regulations to manage the waterway.

They all have a common starting point, namely a detailed comparison of the likely costs of moving on the waterway versus moving by some "least cost" alternate mode. Typically, this comparison involves a detailed analysis of all costs associated, including: Rates paid, special facilities constructed, loading, unloading, time-in-route, inventory costs, etc. Somewhere within each paper this comparison is reduced to a single number, frequently called the "gross rate savings". If this number is negative the alternate mode is the logical economic choice, and it is typically assumed that the movement will not use the waterway. If the G.R. S. is positive, the movement is a candidate for the waterway. [The third paper considers one method in which this is <u>not</u> the criteria.]

Each of the methods to be discussed is, in someway, a further refinement of each movement's waterway costs. Again, if any modified G.R.S. becomes negative, the alternative mode is the logical economic choice. [The first paper allows "modest negativity" as an observed "real world" phenomena.]

The first paper has one obvious short coming, namely, there is no adequate estimate of the unobserved (potential) movements. If <u>significant</u> improvements are made in the waterway, one would expect that new (unobserved) movements will choose the waterway, but there is typically no information available about "potential" movements. The last two papers are using a market survey, which contains "all potential waterway movements", (some of which will be determined not to move on the waterway in the final analysis) and thus <u>does not</u> have the same problem.

The three papers have names for their approaches, and since these names are more suggestive of the methods used than the titles of the papers, this

review will use those names. The names and related papers are:

Tow Cost Model (TCM) and Marginal Economic Analysis (MEA):
found in- "SYSTEMS EVALUATION"

General Equilibrium Model [First approach] (GEM 1):
found in- "A SYSTEM EQUILIBRIUM MODEL FOR ECONOMIC POLICY ANALYSIS OF NATIONAL INLAND WATERWAYS NAVIGATION"

General Equilibrium Model [Second approach] (GEM II):
found in- "A NONLINEAR PROGRAMMING MODEL TO MEASURE" ECONOMIC IMPACTS OF INLAND NAVIGATION SYSTEMS

This review will begin with a short synopsis of each separate paper, and then proceed with a discussion and comparison of the models, using the "names" above for identification purposes. It is felt that this approach provides better insights into the significant differences in each approach.

A Synopsis of

Draft of "SYSTEMS EVALUATION"
by Ron Keeney, March, 1983

This paer introduces the TCM and the MEA. It covers, in detail, the method of obtaining data, its aggregation for modelling purposes, the approach being taken, the parameters being studied, and the functions of the two computer programs being used.

The data used in this paper is derived from actual waterway movements which are intellegently aggregated into groups of similar commodities originating and terminating in specified stretches of the waterway. [The waterway stretches are called "port equivalents".] The details of individual movements are lost in this process, however the general characteristics are maintained.

The approach being taken in the TCM is to develop a fully computerized "cost of movement" model, which provides a method for estimating "rates". Changes in the waterway cause changes in the "cost of movement" and ultimately are reflected in new "rates". This is a very detailed model, and while the paper continually points out simplifications, the fact remains that the significant elements which affect the cost of moving on a waterway are explicitly addressed. The methods described seem to have only two elements which may lead to problems: (1) The tow-makeup is an "optimization", and can be expected to perform much better than the individual (competing) tow operators. (2) The "delay at locks" function is extremely simplified.

These costs (and others) are passed to the Marginal Economic Analysis (MEA) program, which then:

(A) Determines the "GRS/ton-mile" for each aggregate movement
(B) Ranks movements by "GRS/ton-mile", and selects them one at a time, taking the highest "GRS/ton-mile" first.
(C) Adds a single aggregate movement to the system, examines the systemic

effects of the addition, determines the average cost and marginal cost at this ton-mile level. This step is repeated until the movement list is exhausted.

(D) Develops the following curves:
Marginal rate savings per ton-mile
Average tow cost per ton-mile
Marginal tow cost per ton-mile

(E) Diversion to alternative modes is considered, and if the criteria requires, specified movement having negative GRS/ton-mile measures will be removed from the movement list. In such a case, the model returns to step "(A)" of this list.

The diversion is clearly based on a "market behavior" response in this approach.

One major purpose of this combined pair of programs is to identify the waterway usage which "maximizes social welfare". It would appear the methods employed would lead to a constrained version of this. The constraint is that social welfare be maximized only under the conditions that each movement be subject to the same economic penalties, and that arbitrary exclusion (for what ever purpose) be prohibited.

A Synopsis of

Draft of: "A SYSTEM EQUILIBRIUM MODEL FOR ECONOMIC POLICY ANALYSIS OF NATIONAL INLAND WATERWAYS NAVIGATION"
by Don Sweeney, December, 1983

This paper introduces GEM I. It is an interesting paper which is pointed at two audiences. It presents a useful "market based" equilibrium model, along with a mathematical proof of its properties for the more technical audience. Further, for the more practical audience, it presents the FORTRAN code, sample data, and a very effective case for the "analysis of an entire system" rather than isolated "project analysis" by illustrating the large magnitude of the error.

This paper begins with the classical "gross rate savings" (G.R.S.) and examines the effect of "congestion delays at locks" on these measures. When delays reach such a level that a movement has a negative G.R.S. it is assumed to choose the alternate route. Fractional movements operating at "zero" G.R.S. are assumed to remain on the waterway, and cause congestion.

The paper presents a general analysis of the "benefits" for the system as a whole over a multi-year time frame. It also presents an analysis of the impact of a capacity improvement in one of the locks, both as a "project analysis" and as a "system" analysis, doing a before/after comparison in each case.

The "project analysis" is approximated by using the same data, and assuming the "system" is composed only of the lock being improved. The technique is acceptable only for illustrative purposes, but since the benefits are overstated by nearly 100% it is quite effective.

The paper could be improved for the more practical group by addressing the straight forward reasons that the "project analysis" can provide misleading information. Namely, "project analysis" assumes that the forecast of movements which are likely to benefit from a navigation improvement can be

determined in isolation from the rest of the system. In truth, the effects of the rest of the system on these movements may be such that the movements are not present at the lock in question at some later date. In general, "project analysis" merely provides an upper bound on the benefits. Systems analysis [the best possible analysis of the entire system] further reduces the actors and determines a more likely estimate of benefits.

The final version of this paper may contain such additions.

A Synopsis of

Draft of "A NONLINEAR PROGRAMMING MODEL TO MEASURE
ECONOMIC IMPACTS OF INLAND NAVIGATION SYSTEMS
by Don Sweeney and Michael Healy, February, 1984

This paper introduces two versions of GEM II. It first presents a reformulation of the model presented in Sewwny's earlier paper, adapted to be run under a general non-linear optimization package. As presented in this draft, it has some of the same restrictions as GEM II. Later in the paper it is pointed out that many of these restrictions can be eliminated by direct formulation. For example, the economic effect of an hour's delay need not be uniform for all movements.

The first version introduces constraining equations which turn the "general optimization" into a "market behavior" model, that causes a movement to abandon the waterway only when it has a negative "gross rate savings".

The second version of GEM II relaxes the "market behavior" constraint, and effectively "selects" the movements which would produce the greatest aggregate benefits. This maximizes "social welfare" within the limited scope of the problem.

Both versions of GEM II make use of a non-linear programming package called MINOS, a propriatary package which is available free-of-charge to government agencies because of early government sponsorship. The package undoubtedly has the ability to show the "shadow prices" on the various "constraints", which would target the most restrictive constraints, and thus suggest which delay-causing features should be initially investigated for "improvements". This set of pointers is a valuable addition to the analysis in systems as complicated as those being studied.

A REVIEW OF THE CONCEPTS IN THE THREE PAPERS

The General Equilibrium Model (GEM I) is the most easily discussed of the models presented, and will serve as a good background to the others.

It is apparently used to augment the usual study by determining the appropriate delays at each lock in a system due to the traffic, and to divert movements from the waterway to the alternative modes when these delays are large enough that the waterway becomes the inferior route for a movement.

The presented formulation has the following restrictions:

1. The study of alternative routes has already been performed prior to this analysis, and the "gross rate savings" [versus a waterway with locking times, but no delays at locks] is known for each movement. This "initial" G.R.S. is required to ramain constant during each simulation period. (The fact that the current program assumes this to be constant over a forecast period which is several years long is easily altered to be limited to a single year or season.)

   (A forecastable change in some alternative mode [i.e. the creation or deletion of some rail route], which would result in significant changes in the G.R.S.'s and thus cause significant diversions to or from the waterway upon completion, can be easily handled in the program so modified.)

2. The "cost of one hour's delay to a ton of goods" is a constant which is applicable to all mcvements.
   This implies:

   A. All tows are "standardized", having the same hourly costs for the tow boats and barges, in aggregate
   B. The delay times are sufficiently small so that this "cost of delay" is independent of the value of the goods being shipped.

[As it turns out, this restriction is not a part of the general operating version of the model, but was included in this draft in order to simplify the example problem]

3. A suitable function exists which relates queuing delays to the "total tonnage through a lock". This function (which is: delay = f(tonnage)) can be as complex as desired, as long as it can be algebraically manipulated so as to produce: tonnage = g(delay) [Note: this might be an impossible requirement if one wishes to compensate for the directionality of flows.]

The first restriction is not really a problem, but the "no delays at locks" element will have to be strongly pointed out to those people who are developing the G.R.S., as they basic determinations.

The second restriction is not applicable to the general version.

The third restriction is both important and common to all of the papers presented. It has two components. The first question is whether a simple function can capture most of the elements of congestion delays on one side of a lock. It is probably not too difficult to define such a function. The second question has to do with the ability of such a function to reflect the congestion delays when there are various proportions of "up stream" versus "down stream". This is a much more complicated problem, and is likely to be very difficult to handle.

COMPARING "PROJECT ANALYSIS" TO "SYSTEM ANALYSIS"

It is clearly understood that the comparison of the "project analysis" and the "system analysis" were presented for illustrative purposes. It was used to show that there are problems in doing a "project analysis" when the project is only a small part of the system being affected. There is no doubt that it should have been included, because it is an important part of the paper, and it effectively illustrated a point.

However, there is a distinct possibility that this model cannot be used for "project analysis" because of the problem of trying to determine a suitable "remaining G.R.S. at a single lock" for a movement without having run the full system to determine the amounts to be subtracted at the locks not under study. In this particular case, the movements passing through several locks tend to be those movements which do not pass through the lock in question. [There are only six exceptions to this generalization in this data] Because of this, the long movements simply represent a "fixed bundle of benefits" which are eliminated by comparing "before" and "after".

In this example, the six movements mentioned above pass through either 12 locks or 13 locks, while the remaining movements passing through the lock in question pass through either 6 locks, 5 locks, or 4 locks in total. Clearly one cannot assume that an equal amount of delay can be subtracted from each movement before the analysis is begun. That means that if some adjustment is not made, then the order of inclusion/exculsion can be very different for the simulation shown and the "proper" one.

Again, it is not a severe problem for the purposes of this paper, but since there was no hint of this potential problem (with a caveat stating that it is not worth the trouble for illustrative purposes in mind), one is left with the uneasy feeling that such an awareness did not exist.

HANDLING LUMPINESS IS THE EQUILIBRIUM

Classical equilibrium models (such as TCM/MEA and GEM II) do not address the "lumpy" inclusion/exclusion problem. [This is the problem of trying to determine whether <u>all</u> of a movement moves or doesn't move.] A theoretical problem generally determines the point at which a small fractional increase/decrease will disrupt the equilibrium, because the quantities

involved are "infinitely divisable". The GEM I model has one major practical accomodation to the fact that waterway movements are not only "non-divisable", but are so large that the inclusion/exclusion of one more movement significantly affects the other parameters.

The ordinary case is one where:

A. The tonnage passing through a lock cause a delay of X hours.

B. If the delay is only X hours, there exists another movement, M, which would have a positive benefit if he moved on the waterway.

C. If movement M passes through the lock, the delay will become X+Y hours.

D. If the delay is X+Y hours, movement M would have a negative benefit if it moved on the waterway.

The practical accomodation is to set the delay at X+y, where y is less then Y, but greater than zero. This increment in delay is determined to be the exact amount of incremental delay which would cause movement M's net benefit to be zero, so that he is indifferent as to whether he uses the waterway or the alternative mode. The model handles such a situation by defining:

Upper Limit = Other tons + movement M tons
Lower Limit = Other tons

and shows a "tons through the lock" which corresponds to the required equilibrium delay. This tonnage will fall between the upper and lower limit.

Movement M has zero benefits in isuch a situation, and is functionally not included in the accumulation of benefits. Nonetheless, it has reduced the benefits accruing to the other movements. They are all suffering y more hours of delay than they actually suffer if movement M does not use the waterway, and Y-y less hours of delay than they would actually suffer if movement M did use the waterway.

If movement M is large, and would have an apparently large savings by using the waterway when the dela is X (only the "other tons" are using the lock), but has a negative benefit when the delay is X+Y, then one realizes that Y must be fairly large in this case. And since his apparent savings (when excluded) are large, the y is probably also large. Thus the other movements have significantly reduced benefits calculated for them, because

they suffer delays as though the ficticious tonnage y were sharing the lockages and lengthening the queues. Their benefit estimates are surely conservative.

An illustrative example is available from Page 2 of 4 in Appendix E, where Lock no. 13, in the third simulation period, has the following:

Upper Limit = 23,611 thousand-tons

Lowr Limit = 16,216 thousand-tons (so 7,395 thousand-tons have zero benefits) (probably 4th movement listed in Appx D)

Tons causing delay = 21,521 thousand

Delay = 24.50 hours

Of the 7,395 thousand-tons between the upper and lower limits, 5,305 thousand of them were used in the "tons causing delay" assumption. This results in an estimate of 24.50 hours. If we assumed that the only tons actually passing through the lock were the 16,216 thousand at the lower limit, the delay would be only 4.02 hours. Thus the 16,216 thousand-tons actually moving are suffering an extra 20 hours of delay at that lock due to the "potential" presented by that movement.

This is a practical dilemma which deserves futher investigation. It would seem that the proper answer depends on whether a "marginal" shipment would, in truth, split his shipments between modes because they are equally costly. [Note: He might split shipments between models for reasons of strategy, but this would also apply to those in the "other tons" as well as the "marginal shipment", and fundamentally the problem would remain with some other "marginal movement"]

GEM I model can be easily modified to exclude the "marginal movement", and I judge that to be one of its strengths. All of the other models in these papers (TCM/MEA, GEM IIa and GEM IIb) <u>will include fractional movements</u>.

CONGESTION TOLLS

If we took the above problem, and determined a toll which would make the 7,395 on movement (and all movements with smaller G.R.S.'s which might move through lock #13) choose alternate modes, we would have a proper estimate for a "congestion toll" at that lock. In this particular example, each ton lhas

$0.1431 of delay cost when the delays are 4.02 hours, and $0.8722 if delay costs when the delays are 24.50 hours. If the "marginal movement" is not included at $0.1431 and has "zero benefits" at $0.8722, a toll greater than ($0.8722 - $0.1431) = $0.7291/ton, say $0.73/ton, would prevent him from using the waterway. [Note: a six barge tow at 14,000 tons/barge would have to cough up $61,320, not a trivial sum!)

Since all movements passing through this lock would be expected to pay the same toll, the "benefits" accumulated for the movements using this lock would be slightly lowr than before. The "other movements" would pay $0.73 and still suffer 4.02 hours of delay, making $0.1431 + 0.73 = $0.8731 which is greater than the original $0.8722. But, if the marginal movement would have passed thorugh any other locks on the system, those locks will now have less congestion, and the "other tons" will suffer less delays.

This is not necessarily true, of course, if there are still other "waiting" movements which don't pass through lock #13 (and pay athe toll), but do pass through the relieved locks. One would re-execute GEM I with an assumed $0.73 toll on lock #13 and determine if other congestion tolls are needed. The problem is complex, and this example is merely a simple introduction to "congestion tolls" rather than a solution. There are, however, ways to find such a solution , and GEM II aids in finding it.

In classical economics the "tolls" collected add to the pool of "benefits" because they are "transfer payments". Naturally, the "cost of collecting the tolls" should be subtracted from these "transfer payments" before they are added, and the collection of 20,000 thousand-tons * $0.73 = $14.6 million at a single lock will need additional security measures not normally found at locks. "Billing later" will cause "collection fees", either as actual fees paid, tolls uncollected, or in increased salaries for federal marshals.

Recalling that the original construction of the waterway was a "transfer payment" from the taxpayers to the shippers helps to clear up the general discussion as to whether tolls are a transfer payment.

Tax payers transfer the annualized amount C.

Shippers paid T for transportation before the waterway, and the amount t after the waterway.

The decision to build is if: $T-t > C$, the benefits exceed the cost.

If the amount collected from tolls, x, is taken from the shippers and used to offset annual costs, then:

$T-t-x > C-x$ still holds, and it is still a good decision.

[In this case both the benefits and the costs are reduced by x.]

If one insists that the cost is still C, then one considers x to be a transfer payment, and it is not subtracted from the benefits.

The amount of the toll is not unlimited, because there is also the consideration that a high toll may drive off so much traffic that x is not as big as one had hoped.

Any of the models presented in these papers can evaluate the traffic remaining after a toll is placed in effect. None of them can tell you where to toll and how much each toll should be. But GEM II can provide suggestions when operated as GEM IIa (the "market version") because it can provide "shadow prices" on the capacity of the various locks. Even then, the solution will require many "pick one and try it" situations, and optimality cannot be assured.

GEM IIb (the "pick the best movements arbitrarity" version) can easily indicate the movements which are best to keep on the system. One can then compare this to the original list of potential movements, and study the characteristics and patterns of the movements which need to be excluded. Any type of pattern might show up, and a great deal might be learned.

For example, suppose that three quarters of the traffic to be excluded passes through a single (uncongested) lock, and that none of the "best movements" use that lock. A good solution would be to abandon the operation of this lock which is not, itself, congested.

Such examples are not likely to show up unless the lock is at the end of a system and carries movements which travel long distances (congesting other locks along the way) for small net benefits per movement. Obviously, such a lock would be at the headwaters rather than at the mouth of a river.

WHY MANAGE INSTEAD OF EXPANDING CAPACITY?

The simple answer to this question is that there is a timing problem. The forecasts may indicate that there will ultimately be enough traffic to

compensate for the cost of expansion, and when that occurs, expansion will be proper solution. In the meantime, greater benefits can be developed by managing the waterway.

A word of caution. The "time to build" will not be observed by extrapolating the traffic observed on a "managed" waterway. It can be determined only from a total market survey such as that which is done for new waterways. One must have the "potential movements" which will occur under a dramatically changed waterway, and these are, almost by definition, not currently moving under a managed waterway.

A REVIEW OF METHODS FOR ECONOMIC ANALYSIS OF INLAND NAVIGATION PROJECTS

by

Michael S. Bronzini
Director, Transportation Center
Professor of Civil Engineering
The University of Tennessee
Knoxville, Tennessee

Prepared for

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1. INTRODUCTION AND OVERVIEW

The art and science of analyzing the performance and economics of potential inland navigation projects has advanced considerably during the past 15 years. The methodological issues which have spawned this workshop were barely emerging then, when the basic problem was establishing the fact that better methods of systems anlysis were needed. Thus, any criticism of the methods developed over the interim is, in some respects, unjustified. We run the risk of being accused of attempting to enumerate angels on pinheads. Nonetheless, in the belief that further improvements are both possible and valuable, some comments and suggestions in the nature of a critique are offered in this paper. The fact that criticisms are offered does not imply that this writer is unappreciative of the progress which has been made.

The basics of economic analysis were laid out succinctly and rather well in the slim volume, Inland Waterway Transportation; Studies in Public and Private Management and Investment Decisions, published by Resources for the Future, Inc., in 1969 (1). We have been trying to implement some of the basic concepts set forth there (and, in less applied form, in decades of previous economics literature) ever since. Some of the work along these lines, as properly credited in the workshop papers, includes several studies at the Pennsylvania State University (2, 3), and the Inland Navagation Systems Analsis (INSA) project (4). In general, this body of theory suggests that commodity movements will be diverted from the waterway whenever the cost of using the waterway exceeds the cost of using the next best alternative, be it another waterway route or an overland mode. The workshop papers all describe models which attempt to implement this rule in one form or another.

The paper by L. G. Antle, "An Overview of Waterway Systems Analysis Capability and Problems," traces some of the history of analytical efforts and raises some basic issues. This writer, having been involved in much of the history described in the paper, finds a few minor inaccuracies in the historical narrative. The INSA Commodity Flow Model, to my knowledge, has not been used for any actual application studies at the Department of Energy (DOE). However, it was used for a small portion of the Corps of Engineers 1976 User Charge Impact study. The Transportation Freight Model has had a continuing life outside of the Corps of Engineers. A successor version, called the Transportation Network Model (TNM), was developed for the Department of Transportation (DOT), and was used for the joint DOT/DOE National Energy Transportation Study (NETS). The model was then picked up by the Electric Power Research Institute (EPRI), where it still goes by the name TNM. The NETS and EPRI versions include an equilibrium flow algorithm which will be brought up again later.

The Lock Capacity Function Generator (LOKCAP) was not developed in the INSA project, but rather for the DOT Transportation Systems Center, and then for DOT's Office of the Secretary. The revision to handle double chamber locks was accomplished for the Corps of Engineers. LOKCAP was not used heavily for the Upper Mississippi Master Plan study; that study actually relied heavily on LOKSIM2, which is an advanced single lock simulator. The paper by Keeney suggest that the Waterway Analysis Model was not really used for all of those Ohio River Division studies. Finally, the initial version of the General Equilibrium Model was used for the Upper Mississippi Master Plan study.

Antle brings out the important point that a systems perspective, regardless of the methodology used, offers many advantages. Chief among these is maintaining consistent data and assumptions across different projects and

studies. The recent Corps studies cited by Antle illustrate this value. The problem observed in the Oliver study, where single lock benefits exceeded system benefits, is likely a definitional or double counting problem rather than a fundamental problem with the systems approach (although it is true, of course, that large benefits generated by an improvement at one point can be undermined by excessive congestion costs at other points).

The suggestion of combining the Tow Cost Model (TCM) with the GEM merits further consideration and study. In particular, the TCM might be used to develop refined estimates of waterway operating cost, and the GEM might be relied upon to perform the traffic diversion analysis. However, since there is some overlap between the approaches, and since they could share some common data, further analysis and discussion of this concept must occur before any concrete recommendations can be offered.

The next two sections of this paper comment on the other papers prepared for this workshop. In all cases, references to page numbers, sections, etc., are to those in the draft versions of the papers, which may be different than the final versions prepared for the workshop proceedings. Section 4 describes an alternative to the GEM for finding equilibrium solutions to the waterway traffic diversion problem. The final section gives this writer's observations on the presentations and discussions during the workshop itself.

2. THE TOW COST MODEL-MARGINAL ECONOMIC ANALYSIS METHOD

The "Systems Evaluation" paper prepared by Keeney provides a good and comprehensive description of the TCM-MEA method. The overall approach in this method appears to be reasonable and basically sound. It is data driven and very data intensive, which also makes it somewhat cumbersome and probably expensive to use. The ideas employed all seem very worthwhile, but as the method is reviewed, one can't help wonder whether the same ends could be accomplished with considerably less detail, particularly in the operations area. Nonetheless, it is recognized that this approach is much less detailed than the simulation approach, which it has largely displaced since it was first introduced in the INSA Flotilla model. The discussion in this paper of data inputs and how they actually affect model outputs provides a good example of the insights which are gained into both the system and the model as a complex systems model is exercised over a considerable period of time.

There are some details in the TCM which can be questioned as to their validity and usefulness. A considerable portion of the power of the model comes from its simultaneous handling of all shipments throughout the system, and from its systematic use of lock delay curves. However, other methods (notably, the GEM and TNM) use the same features, so this is not a unique advantage of the TCM. The operation of optimizing tow sizes may be questionable. In the first place, as pointed out in the paper, the TCM does not really look at all combinations of towboat size and tow size; rather only the maximum tow size for each towboat horsepower is used. Secondly, there is already considerable data available on tow size distributions for different waterways, and on the relationships between tow size and towboat horsepower. It would probably be easier and less expensive to simply use these tow sizes

directly rather than employing the TCM optimizing algorithm. This would also make the analysis of fuel consumption effects more realistic, since shifts in the towboat size distribution can be made only gradually over a rather long period of time.

All of the different factors used in the TCM make the model rather difficult to both understand and explain. For example, the computation of the barge load factors for each link is a rather complicated approximation. This writer knows of no independent verification of the calculations used in TCM.

The traffic diversion rule, as implemented in the MEA model, corresponds to the general economic principal stated earlier. One problem, however, is that shipments are diverted all or nothing; there is no splitting of movements between modes, as would be required for exact correspondence with the theory. Since the movements used are actually aggregations of numerous other movements, some split is probably more likely than an all-or-nothing diversion.* Also, the method used to find equilibrium requires trial and error iterations, which could prove to be rather lengthy.

In summary, this method exploits congestion theory, and the network structure of the analysis problem. The method also focuses analytical resources on processing data about and understanding the waterway system itself, which is probably desirable.

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*It was pointed out during the workshop that the current version of the MEA does allow partial diversions.

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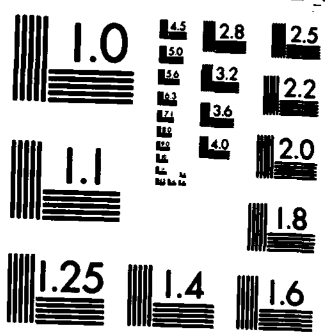


3. GENERAL EQUILIBRIUM MODEL

The paper by Sweeney, "A System Equilibrium Model for Economic Policy Analysis of National Inland Waterways Navigation," introduces and describes the GEM. In a way, this paper is symptomatic of the chief problem with the GEM, in that it is not a satisfactory description of the approach. Someone who is first being introduced to the GEM will actually learn more about it by studying an appendix to the Upper Mississippi Master Plan study (5), or a recent paper by Goicoechea, et al. (6). Many of the comments which follow will be criticisms of the paper, and its companion by Sweeney and Healy, rather than criticisms of the GEM. However, the chief problem with the model is that there has not yet been a serious attempt to explain it in a manner which fosters understanding, belief, and use.

In the first paper, Sweeney indicates that the GEM does not model tow configuration, loading, etc. Indirectly, it does, since waterway operational factors do influence both the supply and demand curves used in the model.

The initial version of the GEM shared the problem of the TCM that origin-destination movements were not split, but were rather assigned all-or-nothing to the waterway route or to the best alternative.

Appendix B in the paper is, again, symptomatic. It is not realistic to believe that someone could use a program source listing devoid of comments to learn about a model. The flow diagram in Appendix A, however, is extremely helpful.

Appendix C reveals one problem with the initial version. If this is a realistic case, the number of iterations required is obviously excessive. There are simple methods which can find the equilibrium for problems such as this in only two to ten iterations. It would also be very useful to have some

interpretation of this example. What do the column headings mean? Did anything significant or interesting happen in this example?

The mathematical description and proof in Appendix F have some problems. The first page has enough description interspersed with the mathematics so that it makes some sense. After this, however, things rapidly deteriorate. Some wording to describe the lemmas and theorems and the general nature of the proofs would be very helpful. For example, Lemma 1 seems to say that, for a given set of nonzero contraint point delays, within a small neighborhood of these delays the movement sets with non-negative and non-positive net rate savings are unchanged. This result seems intuitively reasonable, but the notation in the proof is quite difficult to follow, particularly since many pieces of the notation are introduced without any definition or explanation. Lemma 2, on the other hand, does not seem reasonable at all. It seems to state that, given some movements *which have zero net* rate savings, a small increase in delays either increases the number of such movements or leaves the situation unchanged. It seems that an increase in delays which is large enough to cause some movements with positive savings to have zero savings would also be large enough to cause some with zero savings to develop negative savings. Again, the nonstandard and undefined notation and the lack of descriptions makes it difficult to determine whether the lemma has been interpreted properly, and exactly what is going on in the proof. Some light finally emerges in the discussion of alternative optima at Remark 19. The result that system benefits are constant over all of the alternatives is both intuitively true and also a standard result of mathematical programming.

In contrast to this paper, the description of the fixed point algorithm in the Upper Mississippi Master Plan appendix is intuitively appealing and straightforward. Basically, that description states that we can bound the

system equilibrium traffic on the upper side by assuming that all delays are zero, and on the lower side by assuming that all delays are at the values resulting from the traffic which would occur assuming zero delays. One can see how successive applications of this method would produce a system equilibrium solution, although it might require a large number of iterations to arrive there. This writer believes that there must be a simpler way to both state and prove this result. A simple proof would do much to increase the credibility of the GEM.

The test case given in Appendix G is very good. It truly shows the divergence between local benefits and system benefits.

The paper by Sweeney and Healy does a much better job of defining the GEM. Great care is taken in Section Two to define the nonlinear programming model which will generate the system optimal solution. Unfortunately, this is an irrelevant problem, since the systemic equilibrium is the answer sought. It is recognized that the system optimal formulation is useful in arriving at the system equilibrium formulation. An improvement introduced in this version is that shipments can now be split between alternatives, rather than assigned all-or-nothing. It is interesting to note that the same form of lock delay function is used here as in the TCM and in other methods.

Section Three proports to develop the model to find the system equilibrium solution, which is the one in which we are most interested. Unfortunately, this section reverts to the problems in the earlier paper of using undefined and inconsistent notation without sufficient descriptive material. For example, on page 11, it seems that the authors change notation from $d_j = f_j(z_j)$ to $d_j(z_j)$, but the reader is left to infer this for himself. On page 12 an important equation (3-9) is not sufficiently set out and explained.

From the notation given, the problem statement appears to be very similar to the equilibrium assignment problem which will be discussed in the next section of this paper.

Section four of this paper is another example of the problems with the GEM. The user and analyst cares very little about how the answer is found, once the problem is formulated. He merely needs to be referred to an Appendix with all of the mathematical details, and told that this solution method is very efficient on the computer. The solution method can be studied in depth by those who are interested or who require proofs of the theory.

In summary, the GEM appears to have the right problem formulation, although the model developers seem to go to great lengths to disguise this fact. The excessive mathematical and theoretical shroud which has been thrown over this model is doing it a disservice. If the systemic equilibrium formulation is, indeed, correct, the GEM is a powerful and elegant tool for implementing the general traffic diversion principle stated at the outset. An alternative method of obtaining this result which is both easier to understand and probably much less expensive is suggested in the next section.

4. EQUILIBRIUM ASSIGNMENT ALGORITHM

The systemic equilibrium problem for a waterway transportation system appears to correspond nearly exactly to the network equilibrium flow problem. Consider the following adaptation of the problem and solution method given in (7).

Commodity flows are to be assigned to a transportation network, in which the link costs* are monotone nondecreasing functions of the link flows. Each flow seeks a route which minimizes its own origin-destination cost. The flow assignment is said to be in a user-equilibrium (systemic equilibrium) if no flow unit can achieve a lower cost by switching to another route. Finding this flow pattern can be stated as a nonlinear programming problem. Let

Q_{od} = flow from origin o to destination d

q_i = flow on link i

$c_i(q_i)$ = function relating cost to flow on link i

X_{odr} = fraction of Q_{od} on route r

A_{odir} = 1 if link i is in path r from o to d
= 0 otherwise.

It has been shown that the equilibrium link flows, q_i, may be found by solving

$$\min \sum_i \int_o^{q_i} c_i(x)dx \qquad (1)$$

subject to

$$q_i = \sum_o \sum_d \sum_r A_{odir} X_{odr} Q_{od} \qquad (2)$$

$$\sum_r X_{odr} = 1 \qquad (3)$$

$$X_{odr} \geq 0 \qquad (4)$$

---

*Node costs could also vary with flow. For simplicity and without loss of generality, assume that node costs are zero.

Equation 2 states that the flow on link i must equal the sum over all origins and destinations of the flows that use the link. Equation 3 ensures that the flows over all paths between o and d sum to Q_{od}, and equation 4 states that no flows can be negative.

The objective function, equation 1, is a series of integrals, one for each network link. Each integral is the area under the link cost function from zero flow to flow q_i, the solution variable. This area has no known physical interpretation, but the link flows for which the sum of these areas is a minimum are the systemic equilibrium flows.

This point is illustrated in the simple two link system of Figure 1. The total flow is to be assigned to a waterway route and a parallel rail route. In this case, the waterway cost per unit increases with flow, and the rail cost is constant over all flow volumes. To assign the total flow, Q, the congestion function for the waterway route is plotted over the range (0,Q), and the rail function is plotted in the reverse direction. The intersection of the two functions gives the equilibrium cost, which is equal to the rail rate. The corresponding flows are W and R. At these flows, the area under the two cost curves is minimized. To see this, consider the solution at W'. At this point, the total area under the two curves is the same as that obtained above, plus the small shaded portion. Thus all solutions other than the equilibrium flows produce a larger value for the objective function.

It has been shown that the following algorithm will produce the solution to the nonlinear programming problem. Given a current solution for the link flows, q_i:

1. Compute the costs $c_i(q_i)$ that correspond to the flows in the current solution;

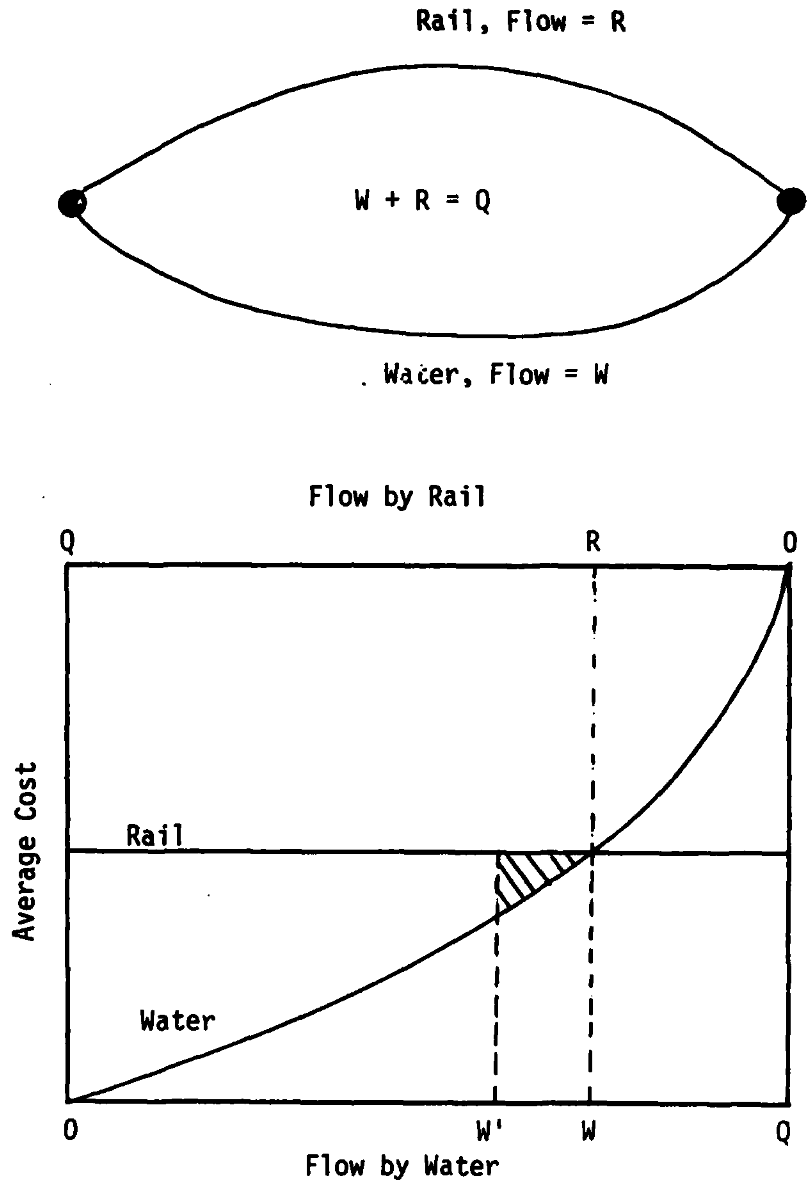


Figure 1. A Two-Route Example

2. Find the least cost paths from each origin to each destination, by using a standard minimum path algorithm and the costs from step 1;

3. Assign all flows, all-or-nothing, to the new minimum cost paths; call these link loadings v_i;

4. Combine the current solution (q_i) and the new solution (v_i) to obtain a new current solution, (q_i') by using a value L selected to minimize:

$$\sum_i \int_0^{q_i'} c_i(x)dx$$

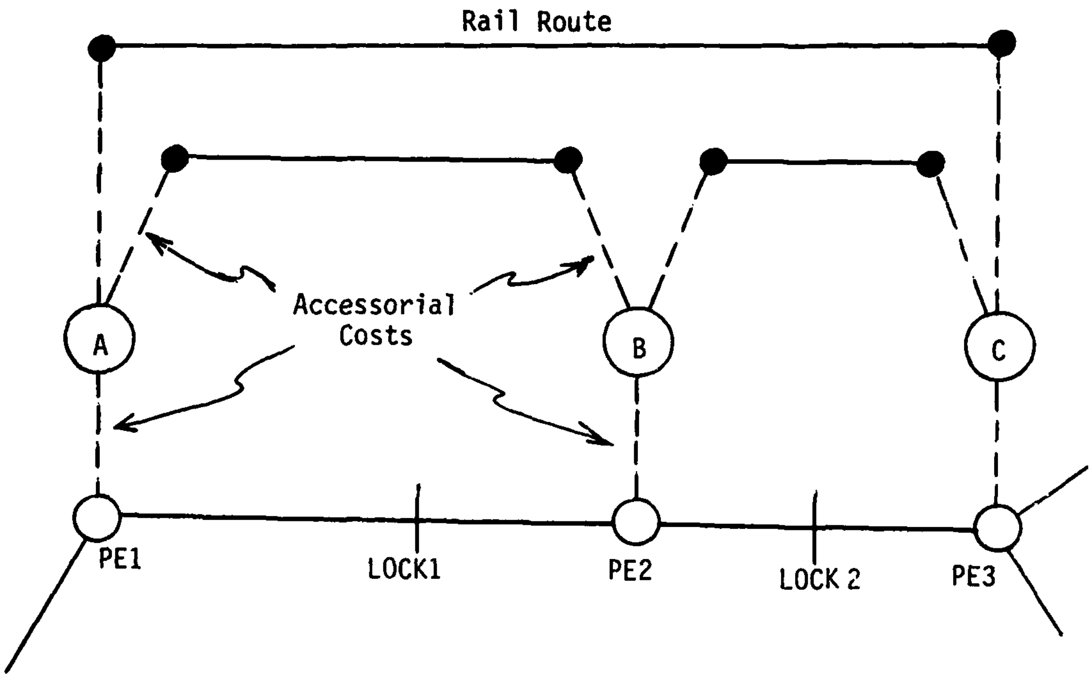
where $q_i' = Lv_i + (1-L)q_i$

5. If the solution has converged sufficiently, stop. Otherwise, return to step 1.

An initial solution can be obtained by assigning all flows to the combined water-rail network assuming congestion-free water costs. This initial solution is then used to compute revised shipping costs to perform another all-or-nothing assignment. The two solutions are then combined by using factor L selected so as to minimize the objective function. Parameter L can be found by a simple one-dimensional search over the range (0,1). Through successive iterations of the algorithm, the value of L will approach zero, indicating that new solutions are adding very little to the ultimate equilibrium flow pattern.

The current version of the Transportation Network Model (TNM) developed for DOT and EPRI, which is the successor to the Corps' INSA Transportation Freight Model, includes software to implement this equilibrium flow algorithm

for freight networks. Figure 2 indicates the type of network which would be appropriate for the waterways flow problem. Descriptions of the relevant software are given in (8) and (9). Basically, this software consists of simple programs which operate on standard TNM input and output files to carry out the steps of the equilibrium flow algorithm. In previous applications, the TNM and related processors have been able to find equilibrium flows for problems with 2,000 nodes, 4,000 links, and 11,000 shipments in two iterations of the algorithm. The vastly smaller and simpler network suggested in Figure 2 and the much smaller movement set used for most Corps studies imply that the TNM will be able to generate systemic equilibria very inexpensively. As a further advantage, the software package produces network loading files and individual movement records in machine readable form, for input into other programs which are being used in the analysis.



To correspond to current Corps practice, this setup uses the actual waterway network and a rail network with direct connections between origins and destinations, with fixed rail rates as the link costs. The actual rail network could also be used.

Figure 2. Waterway and Rail Networks for Equilibrium Flow Algorithm

5. DISCUSSION

The first day of the workshop was devoted to presentation and discussion of the TCM and GEM. The question was raised as to whether these methods compute benefits properly and report them in terms of cost reduction, shift of mode, and shift of origin-destination, as required by the Principles and Guidelines. As presently applied, both methods use a fixed set of commodity origin-destination movements. In this situation, the benefit of a change to the system is properly measured as the total system transportation cost over all modes included in the analysis prior to the change minus the total system transportation cost after the change. Both methods produce this figure, and can readily distinguish between cost reduction and a shift of mode benefits; there are no shift of origin-destination benefits. If the origin-destination pattern is allowed to change with changes in transportation cost, then additional analysis methods will be required.

Several participants observed that defining the equilibrium modal split at the waterway congestion level which produces zero net rate savings ignores all quality of service variables. Conceptually, such variables could be included through application of the total logistics cost concept. It is unlikely, however, that the data needed to implement this approach will be readily available. Thus, restricting the analysis to the low value bulk commodities which normally move by water and basing project decisions on the zero net rate savings concept is a reasonable way to proceed until better methods and data are developed.

Traffic diversion because of waterway congestion is a real phenomenon. There are many shipments which are not moving by water today because of present and anticipated future lock delays.

Sweeney's presentation, in contrast to his papers, eschewed mathematics in favor of describing the background and general motivation for development of the GEM. He cited weaknesses with the large waterway system based approaches (such as the TCM) in the areas of statistical treatment, calibration, traffic diversion, data needs, model verification, and ease of use as the primary motivation for the GEM. He also stated that complex mathematical methods are needed because the problems to be solved are difficult. Although difficult problems might require complex methods, this writer still maintains that the methods can be explained to practicing planners in a manner which does not rely upon trying to make the planners understand all of the mathematical complexity. There are many successful transportation models in widespread use which are complex at the theoretical level, but which are described and understood at a much more intuitive level.

Healy's presentation provided a perfect illustration of the main criticisms of the GEM voiced by this writer. He gave a basic and well illustrated explanation of how the nonlinear programming package goes about taking steps and efficiently finding the solution. This explanation would be of great interest to someone who is concerned with the details of mathematical programming methods. However, it did very little to enlighten the participants about how the GEM works and why they can use it for practical problem solving.

In defense of the materials and presentations by Sweeney and Healy, Antle pointed out that the GEM is of much more recent vintage than some of the other methods described in the workshop. Also, Sweeney and Healy have basically been conducting this work on their own, without benefit of a large cast of supporting analysts. Thus, they really haven't had time to prepare materials for the consumption of a more general planning audience. Nonetheless,

use of the GEM by others will probably not occur until such materials are made available.

After this writer's presentation of the network equilibrium flow algorithm described in Section 4 of this paper (which is not a heuristic, but an application of the well-known Frank-Wolfe decomposition method), Sweeney stated that the equilibrium flow algorithm does not find the same solution as the GEM. This statement is absolutely false. Both methods allocate flows between alternatives such that zero net rate savings are to be had by moving any shipment quantity from one mode to another. It is true that the GEM will find both the system optimal and systemic equilibrium solutions in a single run, whereas the equilibrium flow algorithm would require two runs - one using average cost curves and one using marginal cost curves. It is also true that the GEM produces some useful ancillary output, such as shadow prices.

Keeney observed that both the TCM and GEM use a single delay curve at each lock, which may be to much of an abstraction from reality. The delay curve and the value of delay vary with traffic level, due to the changing traffic mix. This implies that a family of curves might actually be needed to reflect different traffic mixes. It might also be possible to derive a composite delay curve if the traffic mix changes in a regular way with the traffic level. If such regularity does not exist, then iterations of the models would be required to obtain a solution which uses the correct delay curves.

Several principal issues emerged during the discussions. They are as follows:

1. Is the GEM basically a replacement for the MEA, or does it provide additional capabilities? In this writer's opinion, the GEM is basically a

traffic diversion model, so it replaces the MEA. It does provide some additional outputs, but these are secondary in comparison with its primary function.

2. Does the GEM require less data than the TCM-MEA approach? Sweeney believes that the answer is yes, since much of the data required for the TCM is not input to the GEM. However, the GEM uses inputs which rely on the same underlying data as the TCM, either implicitly or explicitly. Thus, there is not really much of a data requirements gap between the two approaches.

3. Do the rankings of shipments in the TCM according to rate savings per ton or per ton-mile produce different traffic diversions, and does this ranking method preclude use of the model for analyzing a congestion toll? This issue arises because it removes some of the simultaneity in the treatment of shipments which might be required for a proper analysis. This issue requires further investigation before any recommendations can be made.

4. Does the TCM account properly for backhaul economics? In particular, if the MEA diverts a shipment which is a front haul, what does that do to those movements which might have been part of the backhaul for the diverted shipment? Further explanation of the backhaul treatment features in the TCM is required if other analysts are to adopt this method.

The meeting concluded with a discussion of future research priorities. In addition to the issues discussed above, research appears to be needed in the following areas:

1. Development of consistent and theoretically sound commodity flow projections for Corps project studies;

2. Improved documentation of the methods and results used by the Corps for deriving vessel operating costs for use in economic analysis;

3. Investigation of alternative modal split methodologies, particularly those which are able to incorporate variables in addition to rate savings; and

4. Development of improved data on the environmental impacts of water traffic and development of methods to tie the environmental impact analysis to the economic analysis.

Significant work on some of these topics is already underway.

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Final Draft

ECONOMIC EVALUATION OF INLAND WATERWAY PROJECTS:
A DISCUSSION OF ALTERNATIVE
SYSTEM ANALYSIS MODELS

Dr. Leonard A. Shabman
1901 Meadowview Circle
Blacksburg, VA 24060

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INTRODUCTION

Benefit evaluation for inland waterway improvements has been a subject of attention in the water resource economics literature for a number of years. As a result several important evaluation principles, and suggestions for practical application of these principles, have been developed and recently incorporated into the Water Resource Council's Principles and Guidelines (P&G). At the same time district offices of the Corps of Engineers have been faced with the challenge of evaluating proposals to improve and repair the existing navigation system. Improvement and repair plans are often motivated by the concern that navigation projects designed in the past are now suffering congestion from traffic growth and may need to be better managed and/or expanded.

Corps of Engineers' field offices have sought to develop conceptually valid models for evaluating the economic efficiency (National Economic Development, or, NED) benefits of management and expansion plans for congested waterways. One model, presented at this workshop by Keeny, has been applied to the Ohio River navigation system and is, hereafter, termed the "ORD Systems Analysis Model". An alternative approach, presented at this workshop by Sweeny, is termed the General Equilibrium Model (GEM); the MINOS solution algorithm for GEM uses non-linear programming techniques. Hereafter this model will be termed GEM/MINOS.

The purpose of this workshop is to compare and contrast the GEM/MINOS and ORD models. This paper will compare the model's validity for economic benefit estimation. To provide a basis for this comparison, a basic economic framework for navigation-benefit estimation is first developed.

FRAMEWORK FOR BENEFIT EVALUATION

Focus on Systems Analysis

The ORD and GEM/MINOS models under discussion at this workshop are designed to assess a similar evaluation problem:

> Determine the national economic efficiency benefits for capacity expansion and/or capacity management on an inland waterway system:
>
> (i) when any single improvement to relax a system constraint does not stand in isolation from other capacity constraints, and therefore,
>
> (ii) it is necessary to consider the economic costs of delay at all locks as part of the evaluation of any single project.

Two observations about the economic content of the ORD and GEM/MINOS models can be made at this point. First, the consideration of delay as a system-wide, as opposed to project-specific, relationship is a problem of queueing analysis to be addressed by operations research techniques. The queue considered is for the waterway segment rather than a project within the segment. The problem for economic analysis is the measurement of economic penalty of delay in the queue. Therefore, this discussion of the economic framework of the ORD and GEM/MINOS models will assume that the queue analyses accurately reflect the extent to which relaxing a constraint at one point in the waterway system will shift time delay to other constraint points.

Second, the models are designed to assess economic benefits of expansion and management changes on congested waterways. Antle, in his paper for this workshop, suggests that economic evaluation of repair and replacement of uncongested locks may become a problem of significance in the future. The ORD and GEM/MINOS models might be adapted to consider

this evaluation question, but that is not their focus at this time. Furthermore, the economic framework presented below is not addressed to the repair/replacement problem.

Economic Evaluation for Congested Waterways

When changes in waterway system management or capacity reduce the national resource costs of transporting goods, an NED benefit is realized. These cost savings would be reflected in the willingness-to-pay of shippers and barge operators for the waterway improvement.

The barge industry is highly competitive; in addition, the long run industry supply curve is, most likely, highly elastic. As a result, barge operators could be expected to earn normal economic profit. Congestion raises barge operator costs causing shifts in the long run supply curve and in barge rates. Thus, from the perspective of the barge industry, NED benefits which might be realized by reductions in congestion are barge operation cost savings. Congestion also affects the demand for barge transport by changing shippers profits (willingness-to-pay) from use of the barge mode. Therefore, the total NED benefit for the relaxation of congestion on a waterway is the sum of barge-operation-cost reductions plus the increase in shipper profits.

Measurement of these changes is the objective of the ORD and GEM/MINOS Models. However, before assessing the models directly, it will be helpful to have a simplified economic model of navigation system improvement as a reference point. This model begins with an examination

of single shipper demand for a single transport mode and then draws inferences for the multiple shipper and multi-mode case.

Six determinants of transportation demand are considered in this model: 1) the shipper's (transport demander's) cost of production, 2) an interest rate, 3) the rate charged for line-haul transportation, 4) associated costs of transportation, including cost for handling and loading facilities; also, a subjective "quality-of-service" difference, as an economic penalty for the low "quality" mode, is included in associated cost, 5) average travel time for each mode, and, 6) the market price for the commodity being shipped. Each producer is assumed to know the price he will receive for this product at the market. Also, revenues from sales are received only after the product reaches the market. Using the following notation, a firm's demand <u>for a single transport mode</u> can be developed:

$ = the shipper's profit

Q = the quantity it shipped

P = the market price of the product shipped

a = time in days to ship the product from point of production to point of sale

R = transport rate per unit of output for line-haul movement

A = associated shipment costs

i = interest per day

The shipper's profit is:

$$\$ = \frac{(P-[R+A])Q}{(1+i)^a} - f(Q)$$

where: f(Q) is the total cost of production.

The numerator of the first term is revenue from the sale of the product less transportation cost. Since revenue is received only after a days, the division by $(1 + i)^a$ puts the net revenue figure on a present value basis. The decrease in net revenue which occurs if a is greater than zero represents an inventory charge.

Differentiating profit with respect to Q and setting the result equal zero gives the marginal cost equal marginal revenue profit maximizing condition.

$$\frac{d\$}{dQ} = \frac{P - [R+A]}{(1 + i)} - f'(Q) = 0.$$

Letting R be variable, while holding P, A, i, and a constant, traces out the firm's demand schedule for transportation, with quantity of goods produced and transported being an inverse function of R. Also of interest is that the transport cost components, A, i and a, are transport demand shifters with quantity shipped increasing as their values fall for any given value of R.

Letting $P_t - [R_t-A_t]/(1 + i)^a = \hat{P}_t$, a demand curve for transportation can be developed graphically for values of R_t, given the usual assumptions about the shape of cost curves. Alternatively this transporter's demand curve will be termed the shipper's marginal profit function, relating changes in line haul rates to changes in shipper profits. This is shown in Figure 1-A and 1-B.

In Figure 1-A production costs and net product prices are measured on the vertical axis, while Q on the horizontal axis is the quantity the firm would produce to ship at a constant price P and at

variable levels of R. $\hat{P}_m$ shows the quantity shipped if the transport charge were zero. The price received would just equal the product price at the market, and marginal revenue would equal marginal cost at quantity Q_m. As R increased from zero to R_3, R_2 then R_1, $\hat{P}_t$ would get smaller corresponding to $\hat{P}_3$, $\hat{P}_2$ then $\hat{P}_1$, in Figure 1-A. In Figure 1-B the rates R_3, R_2, R_1 are shown with the corresponding quantities shipped. At A, R_t rises to the point where $P_t - [R_t+A_t]/(1 + i)^a$ is just equal minimum average cost. Therefore, at rates higher than R_1 no transport will take place.

Now reinterpret Figure 1-B as a shipper's inter-modal choice problem where only line-haul transport rates affect the profit realized from a modal choice. In effect, this assumes that A, i, and a are identical for the alternative modes. Letting R_3 = barge rate and R_2 = rail rate, quantities produced and shipped are Q_3 and Q_2, respectively. The increment in shipments at rate R_3, Q_2Q_3, may move to the same market or to a different destination, although the waterway segment would be used for part of the transportation link. The incremental profit from selecting the barge mode is R_3R_2BC. This area, given the linear marginal profit function, can be derived from equilibrium rate and shipment information. That is,

Equation 1:

$$R_3R_2BC = ([OQ_2]*[R_3R_2]) + \frac{Q_2Q_3}{2} *[R_3R_2]$$

If rates equal marginal shipment costs for each mode then the area R_3R_2BC is the NED benefit of the barge mode's availability. As the

marginal profit function (e.g. transport demand curve) becomes more inelastic, the product of rate differences times total shipment levels by barge (OQ_3) becomes an increasingly accurate approximation of NED benefits. The transport demand function will become more inelastic as line-haul rates become a smaller portion of total production and shipment costs. It would be necessary to predict equilibrium traffic shipment levels at each rate in order to compute the NED benefit.

Figure 1-B can be extended to an evaluation of NED benefits for reduction of congestion, when rates charged equal marginal costs, including costs of delay. Also, the assumption that only line-haul rates affect model choice is retained. Figure 2 provides the basis for this discussion.

Congestion on the waterways raises barge costs and, therefore, rates form R_3 to R_4. As a result shipments fall in relation to rate-elasticity of the marginal profit function; not as the differential between rail and barge rates. Reduction of congestion by capacity expansion yields benefits R_3R_4FJ. This area could be approximated by predicting the barge rate and shipment level with versus without congestion, and then computing the NED benefit. That is,

Equation 2:

$$R_3R_4FJ = ([OQ_4]*[R_3R_4]) + \frac{Q_4Q_3}{2}*(R_3R_4)$$

Now retain the assumption that only line-haul rates affect shipment levels and modal choice, but expand the perspective to multiple shippers

and multiple commodities on a particular waterway segment. In the uncongested waterway case, the use of the waterway by any shipper is evidence that the rate-differential between barge and rail results in increased shipper profits. For any shipper this is calculated using Eq. 1, above. These individual shipper profits can be arranged from highest to lowest, with total tonnage shipped accumulated on the horizontal axis of Figure 3. This yields an aggregate incremental profit function (AB) for all shippers using the waterway. (The increment is the profit increase from having barge transport available.) The area under the function AB is the total benefit to all shippers for use of the waterway. (Actually the smooth function shown would be a step function given the manner in which the calculation is described.) Note that the area OAB is approximated by the product of rate-differences times total quantity shipped by barge as the rate-elasticity of the marginal profit function becomes smaller.

On a congested waterway segment, the function CD would be developed, where the reduction in shipper profit is computed by the formula in Eq. 2. The aggregate gains from capacity expansion would be CABD in Figure 3; shipments would rise from OD to OB.

A more realistic modal choice analysis would consider associated cost (A) and speed (a) differences between modes for each shipment. The result is that the marginal profit functions of Figures 1-B and 2 will be different for different modes. Figure 4 illustrates this situation.

In Figure 4 the rail mode is shown to yield higher profits, at any given line haul rate than the barge mode, because of quality of service, speed, and associated cost advantages. However the barge mode is able to offer lower line haul rates at R_3 versus R_2. In this case the shippers choice to use rail leads to R_2BD profit; the choice to use barge yields R_3AE profit; ([R_3AE] - [R_2BD]) is the incremental gain from barge mode availability. Given that both modes are marginal cost pricing, the NED benefit for the barge mode is also the difference in these two areas. Note that the shipper would split traffic among modes where the difference R_3-R_2 is less than the money amount of the marginal profit function shift. Thus, modal split would occur before rates are equal.

Computation of the incremental profit of barge versus rail shipment would require quantification of the money effect of a, A and i on shipper profits, in addition to knowledge of comparative transport rates and the rate elasticity of the transport demand function. First, for shipment OQ_2 that would otherwise move by rail, the benefit is ([R_3R_2]*[OQ_2]) - [ABDGC]. The area ABDGC is the profit reduction from use of the barge mode and can not be measured by rate comparison. The area FGE, the benefit for shipment of Q_2Q_3, also can not be measured by rate comparison, but is part of the benefit analysis.

Figure 4 clearly demonstrates that modal choice, and quantity shipped on a waterway, can depend upon the multiple factors affecting shipper profit included in the discussion of Figure 1-A and 1-B. However, it must also be recognized that associated costs for each mode

are typically fixed investment costs that, once made in order to take advantage of a mode, will cause a shipper to remain with a particular mode until that investment is economically depreciated. Thus, traffic response to rate differentials is not a perfectly "reversible" process. With existing traffic on a waterway, where associated costs are sunk, the profit differential between alternative modes becomes smaller. Indeed the functions may reverse their position from that shown in Figure 4 if a switch to the rail mode requires investments to cover associated costs that would not be made if waterway traffic continued. The results is that the "short-run" response of waterway traffic to rate changes may be quite limited. Indeed, barge rates could even rise above rail rates and traffic might remain on the waterway in the short run. When new traffic is being considered for the waterway versus rail, then comparative associated costs will enter into the modal choice decision. Here the response of traffic to rate differences may be greater.

Finally extend the analysis in Figure 4 to include congestion. This is done with Figure 5. From Figure 5 two important observations are in order. First, with congestion it is possible that equilibrium shipments may not change even if the barge rates rise above the rail rate; alternatively, the switch may occur before the rail and barge rates equate. The equilibrium quantity shipped on the waterway will depend upon the congrestion induced shift in the marginal profit function for barge relative to the congestion induced change in the barge rate.

Second, the economic penalty of delay must be interpreted as more than the incremental addition to barge rates. While the increased barge rate subtracts from shipper profits, the full economic penalty of delay is the cross-hatched area in Figure 5; that is, this shipper's willingness-to-pay for reduced congestion includes more than expected rate savings and will depend upon the rate elasticity of the profit function and the functions elasticity with respect to comparative levels of a and A for the alternative modes. Thus, individual shippers facing the same rate increase from congestion may have wholly different shipment responses and different benefits from reductions in congestion.

Following the same arguments used to develop Figure 3, the without congestion incremental shipper profit (rail vs. barge) can be developed as functions AB and CD in Figure 3. However, congestion costs will not be a uniform shifter of AB to CD in the case where non-line haul rates affect shipper profit. Thus, with congestion the order of shippers along the horizontal axis can be rearranged at the same time that the profits for each shipper are reduced.

A Note on Management of Congestion

Whenever barge rates do not rise to reflect the full marginal cost of delay (congestion) it is possible to have economic efficiency gains from traffic management; this possibility must be made part of the benefit evaluation process. A divergence between average delay cost for barge operations (ADCO) and marginal delay cost on the system (MDCS) occurs when the decision of one barge operator to add a tow to a water-

way segment does not consider (i) the increase in operating costs from delay which are imposed on other barge operators and (ii) does not include the reduction in shipper profit from such factors as increased inventory charges. As a result, the average delay cost will be the basis for operators barge rates, will rise with traffic levels, and will include only changes in barge operating costs and not the effect on shipper profits.

In Figure 6 a barge rate R_3, with no waterway congestion is shown at level of shipment Q_3. At Q_3 congestion occurs and delay costs rise along ADCO and MDCS. For development of Figure 6, individual shippers' barge-transport-demand curves are for an uncongested waterway situation. The sum of the shipper demands gives aggregate demand for an uncongested waterway. Dd^1 is original demand; however, a shift to Dd^2 causes congestion to occur. In an unmanaged waterway there would be barge rate R_5 and shipments of Q_5; however Q_6 is the shipment level which maximizes aggregate net returns to shipments on the waterway. From Q_6 to Q_5 the gains to shipping on the waterway as the area under Dd^2 are less than the delay costs imposed in the system.

Two points can be made about this situation. First, a congestion fee could be imposed to result in Q_6 equilibrium. However setting such a fee would require knowledge of the economic penalty of delay at Q_6 which includes both increases in barge operating costs and reductions from shipper profit.

Second, the benefits of capacity expansion would need to consider several possible conditions. The with project condition would be

traffic at equilibrium level Q_5; three project alternatives would exist. One would be to institute traffic management to attain Q_6. A second alternative would be to expand capacity of the waterway shifting MDCS. Benefits would equal the sum of delay cost savings for existing traffic plus benefits earned by new traffic. A third alternative would combine traffic management with a structural alternative. The benefits for each alternative would be compared with the cost of the alternative.

A COMPARISON OF SYSTEM MODELS

The Solution Approaches

(1) The ORD and GEM/MINOS models are both solution algorithms for economic analysis of capacity expansion on a congested waterway. The conceptual approach to benefit measurement is the same for both models. At the most general level each model identifies a barge "transport demand" function and uses that function, in conjunction with measures of average delay cost and marginal delay cost, to find equilibrium system traffic levels. By varying delay on the system through capacity management or capacity expansion, new equilibria are discovered and benefits of a project can be computed.

More specifically, both model approaches use a similar stepwise procedure for benefit estimation. Both begin by identifying a study area and set of commodities that might potentially move on the waterway at different time periods. Then based upon consideration of comparative transport costs the potential traffic is "split" between the waterway and alternative modes. Included in transport cost is the current level

of congestion as it affects barge rates. Then reductions in congestion and barge rates from capacity expansion and/or system management are used to project how traffic would change with changes in barge rates, including, or excluding congestion fees. Benefits are computed as the changes in line-haul transport costs with versus without the waterway improvement.

However, the models do differ in the manner by which equilibrium traffic levels are discovered. This can be easily illustrated by Figure 7 which is derived from Figure 6. The ORD solution procedure develops the transport demand function (Dd) as the transport rate savings on the system, as this was described for Figure 3, above. The MDC functions are developed from barge operating cost data . Then using an iterative process alternative points on the functions are compared until point B is discovered and traffic level OC is found. The details of this search process have been described the model's developers in this workshop.

GEM, using MINOS, procedes directly to a search for point C. It does this by developing data on barge transport demand, which it also defines as a line-haul rate saving from use of barge over rail, and delay cost. Then MINOS, which is a non-linear programming algorithm, selects that traffic level which maximizes net transport cost savings; that is the problem is to find that level of traffic which maximizes ADB.

I am inclined to favor the MINOS mathematical programming approach to this solution problem because, in a systems framework, the shadow values it yields can provide useful analytical information. For example, the shadow value on a passage at the various locks in a system

answers the question of which lock would yield the greatest return if expansion of capacity was made. This same information would only be available by trial and error if the ORD model sought to answer the same question. Beyond this argument, choice between the solution approaches seems to hinge upon their computational validity -- a matter for others to discuss.

(2) In their current form, it appears that ORD and GEM/MINOS call for different data inputs to derive their solutions. GEM/MINOS has data requirements limited to rate information, system delay relationships, projected tonnage, and costs of delay. The ORD model, which draws upon the tow-cost model, requires far more data to evaluate how tow-cost and barge rates will vary with system configuration and delay.

All other factors equal, the less data demanding a model the more useful the model. With a more complex data base it is difficult to evaluate the "intuitive" validity of a model solution. Also, it is more likely that failures to have accurate measurement of several less significant model parameters will result in a compounding of errors leading to inaccurate model solutions. However, as will be seen below, the limited data called for by the current version of GEM/MINOS may limit its conceptual validity. Nonetheless, the GEM/MINOS model could be expanded to include a data base of more detail. Indeed a data base identical to that used by the ORD model could be used.

While the ORD model uses a larger data base it would not necessarily provide a more valid measure of benefits than GEM/MINOS from that base. Whether a data base is large or small, detailed or general, begs the

more fundamental question of whether its content and use provides a conceptually valid analysis. At one extreme it is possible to devote too much attention to "calibration" of the model's data to the actual system being modeled. The result is that the attempt to consider "outliers" in the data will result in failing to isolate the underlying patterns of behavior in the actual situation. This may be a problem with the ORD model.

A second, and more serious problem, is that attention may be directed to refinement of data which is relatively unimportant for developing a conceptually valid model. Meanwhile important areas receive little attention. As one example, the attention in the ORD model to precise estimation of barge operating costs seems out of proportion to the consideration given to traffic projection.

<u>Benefit Measurement</u>

(1) When evaluating benefits the principle to be followed is that the reduced value of the nation's resources required to transport commodities is a part of the measure of project benefits. To employ this principle requires that line haul resource costs to move commodities by alternative modes be estimated. The P&G suggests that, subject to certain considerations, the transport rates for other modes can be used to approximate the marginal cost of the alternative. The GEM/MINOS model's documentation provides no discussion of rate selection. The ORD model describes a complex procedure for rate determination of alternative modes and for rate comparisons. Several issues of importance are

addressed by the ORD model, including seasonality and the consideration of non-line haul cost differences in the total cost of shipment. However, it is not possible to determine from the materials provided whether the "rate matrix" approach used for the ORD model develops rates that can be defensible proxies for the marginal costs of shipment on alternative modes.

(2) The calculation of benefits of delay reduction in both models is based upon line haul cost savings for a shipment expected to move over the waterway if that shipment would otherwise have moved by an alternative mode. The cost for the alternative mode is the same with versus without the project and the rate for the congested versus uncongested waterway movement varies with level of delay.

The ORD model relies upon a submodel for tow-cost estimation to estimate barge rates. This sub-model incorporates delay induced changes in waterway line-haul costs directly into barge rates; benefits appear to be computed on the net difference of rail rates less barge rates with versus without the project.

Both models seek to provide estimates of benefits that conform with the P&G through stepwise procedure described earlier. In this procedure various, largely unspecified, approaches to projecting traffic on the waterway without a project are used. For the projected traffic the difference in line-haul rail rates and line-haul barge rates is the unit transport benefit per unit shipped by water. Both models arrange these unit benefit estimates from highest to lowest and generate a rate savings function which is termed the "barge transport demand function."

The area under the function is the benefit of the barge mode in the without project condition. Because these calculations are based on rates and are derived as they are, two potential sources of error exist. First, this approach assumes a perfectly inelastic shipper profit function. If this is not the case, then benefits are overstated. The previous discussion of Equation 1 illustrates this point. Second, if there are non-line haul differences in shipper costs then rate comparisons alone will misstate the benefits of the barge mode over the rail mode. Consideration of these factors in initial traffic projections only partly accommodates this consideration. Referring to Figure 4. such consideration would result in traffic projections at Q_2 rather than Q_N, but would not automatically consider the difference in unit shipper profits from 0 to Q_2. The GEM/MINOS model seems to ignore this point. The ORD model has a data base that could include this consideration, but I am not certain it is used in this manner.

Benefits for a with project condition (eg., reduced system delays) are computed by both models in a similar stepwise manner; barge rates fall as delay falls, traffic levels induced by the lower barge rates are set, and the difference between the rail rate and new barge rate is computed to be the with project benefit. The difference in barge vs. rail shipment benefits with versus without the project is the benefit of the project.

These steps add a potential of additional error. Both models compute the economic effect of congestion entirely in terms of barge operating costs and tow rates. However, to the extent that demand

shifts with congestion, the economic cost of delay is misstated by this computational approach. See the discussion of Figure 5, presented earlier.

In general, the models compute benefits in terms of transport rate savings without regard to the elasticity of the transport demand (shipper marginal profit) curve and without regard to the multiple factors that contribute to differences in transport cost. However, the benefits computation procedures are consistent with the P&G; therefore, it is the P&G that may need further examination. Also, it appears that much of the data which is now part of the ORD model could be incorporated into more conceptually valid benefit estimates. What must be recognized is that the error in benefit computation will be smaller as the following implicit assumptions are valid: (i) an inelastic transport demand curve, (ii) zero differences in non-line haul costs for an equilibrium traffic level, and (iii) unimportance of congestion/delay as a barge- transport-demand shifter.

Measurement of Delay Costs

(1) The GEM/MINOS approach explicitly only considers the effect of delay on barge operating cost. It incorporates delay cost increases or decreases into its model by adding or subtracting a delay cost penalty to barge rates which exist in the without project condition. Thus, barge rates move up or down with delay by the addition or subtraction of delay cost. (Of course a more complete measure to delay cost could be developed for the model.)

The ORD approach also considers delay entirely in terms of barge costs and rates. It uses its tow-cost sub-model to estimate barge costs both with and without the project. A ratio of current barge rates to barge costs for the without project condition is computed. This same ratio is used to predict the change in barge rates with computed changes in barge costs with the project. The result is that the ORD model's barge rates move more with delay cost changes than is the case in GEM/MINOS. The comparative validity of these two approaches needs to be verified by empirical analysis of the relation of observed barge rates to observed changes in congestion.

(2) As noted above neither model considers the effect of delay as a shifter of the barge-transport-demand function, or, alternatively stated, as an economic cost of congestion which is not reflected in barge rates. In the context of Figure 5, neither model apparently considers shippers' profit loss as a function of delay, and therefore as a component of the cost of delay. Instead the increment to delay cost from congestion is limited to changes in barge operating costs.

Modal Choice

Both models have apparently similar modal choice frameworks. Initial traffic projections are made by unspecified methods from outside the model. Then traffic is projected to change with delay cost in terms of rate savings changes; that is, when barge rates change with delay costs, traffic enters or leaves the waterway until the marginal shipper realizes zero line-haul gross-rate savings from choosing the barge mode

over the next most costly alternative. Thus one problem for modeling the choice of modes is apparent. If non-line haul cost considerations enter into modal choice, they do so only at the point where initial traffic projections are made. After this point, incremental adjustments to changes in delay are limited to responses to shifts in line-haul rates. However, as was noted earlier, traffic on a waterway may be quite unresponsive to rate changes, if costs of changing modes include more than simply the line-haul rate of the competing mode. In more general terms, the rate elasticity of demand for a mode is not carefully considered by these models. As a result (i) modal choice may not be appropriately simulated, (ii) the traffic response to congestion fees may not be accurately simulated.

FINDINGS

This paper briefly reviews the ORD and GEM/MINOS navigation system models. The comments reflect this author's current understanding of how these models operate. However, papers that were made available to describe these models were neither well organized and/or of sufficient scope to convey the essential features of each model. Although presentations at the workshop did help to clarify some confusing points, the findings which follow are only tentatively offered.

- Both models would need to be carefully adapted to be able to deal with benefit estimation for repair or replacement of existing

locks. Currently the models are focused upon evaluation of delay reduction.

- Both models need to be more carefully presented. A conceptual foundation for the models should be carefully developed as a basis for defending the model's strategies for waterway traffic estimation and benefit measurement.
- Both models use line-haul rate savings from use of barge over an alternative mode as the transportation demand function. This approach has several conceptual weaknesses which can affect the models traffic and benefit estimation solutions.
- Both models use a limited concept of cost for measuring the economic penalty of delay.
- Both models have problems with their required data bases. It appears that GEM/MINOS has too limited a data base to provide conceptually valid solutions. The ORD data base is far richer, but may place emphasis on low priority areas for data refinement.
- Both models depend upon traffic projections made outside the model, but no clear statement of how projections should be made is offered.
- Both models provide estimates of benefits which are consistent with P&G guidelines. However, the P&G may not offer adequate guidelines for the evaluation of improvements on congested waterways.
- Both models assume rates equal marginal cost of transport but do not provide a defense of this proposition.

- Both models translate delay costs to changes in line-haul barge rates. However this is accomplished in different ways and it is not clear which is more valid.
- Both models have a traffic diversion/attraction rule limited to line-haul rates. This is probably an inadequate representation of reality.
- The MINOS solution algorithm is more desirable than the ORD method of model solution because it provides useful shadow price information.
- The necessary detail to better model delay cost effects and modal choice may already be included in the ORD data base. For example, inventory charges may be computed for delayed shipments. However, it is not clear that this is now properly inserted into the model solution process.
- Several issues with regard to transport-rate-elasticity of demand are raised in the text of this paper. These issues include a need to more carefully examine:
  - (i) modal choice behavior for new movements and diversion of traffic from existing movements
  - (ii) quantification of the relative importance of rates versus other costs in transport demand.

Figure 4

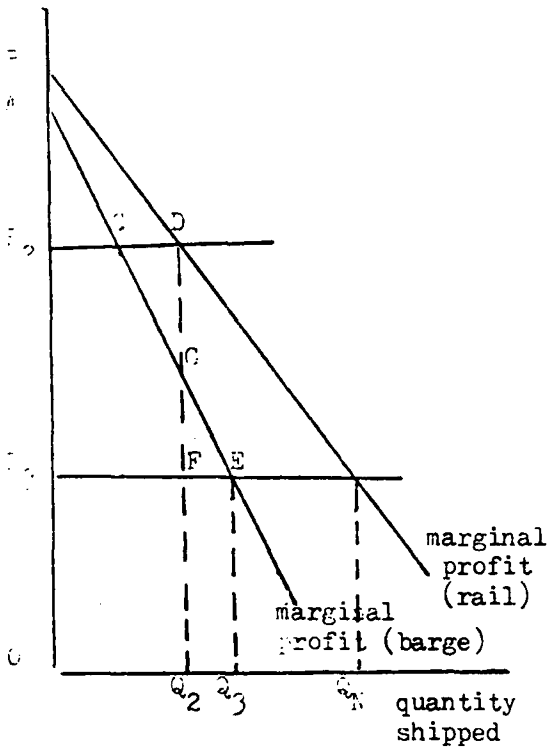


Figure 5

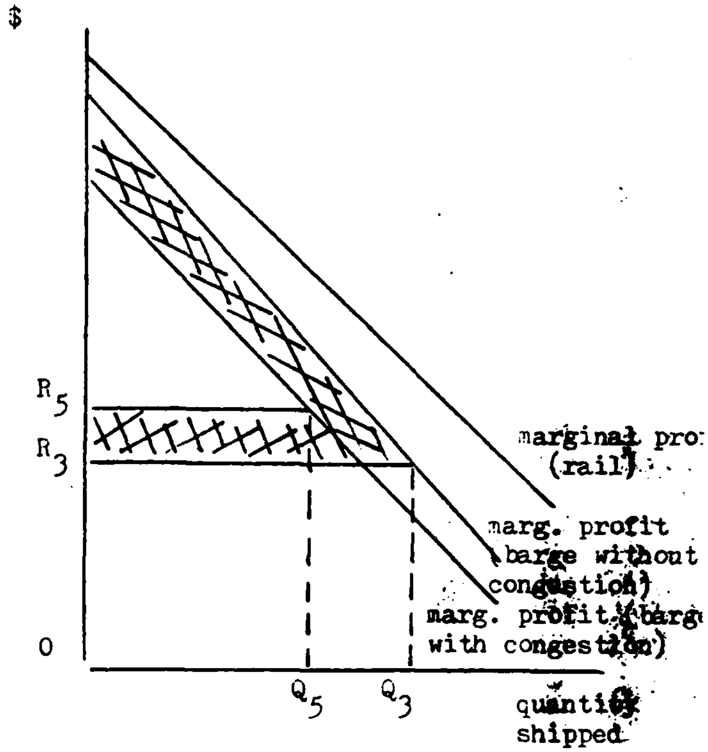


Figure 6

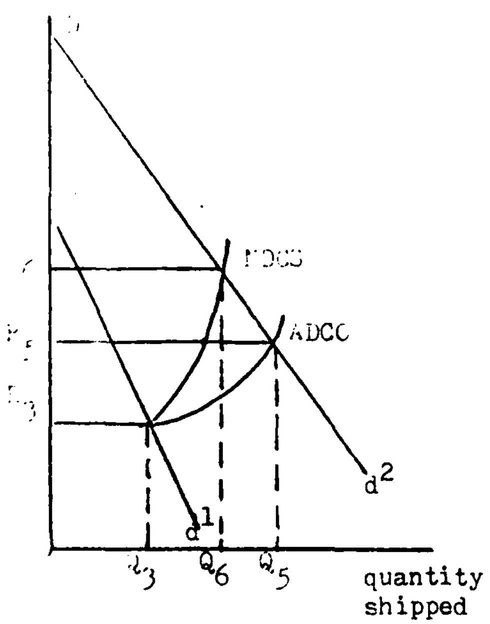


Figure 7

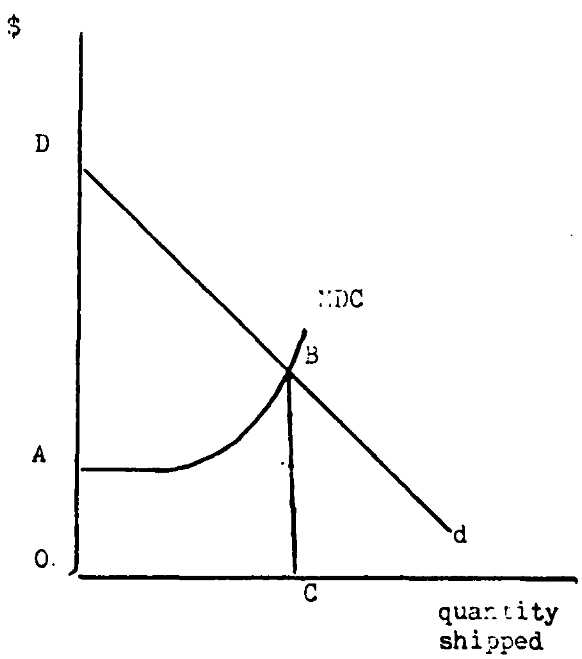


FIGURE I
Demand for Transportation

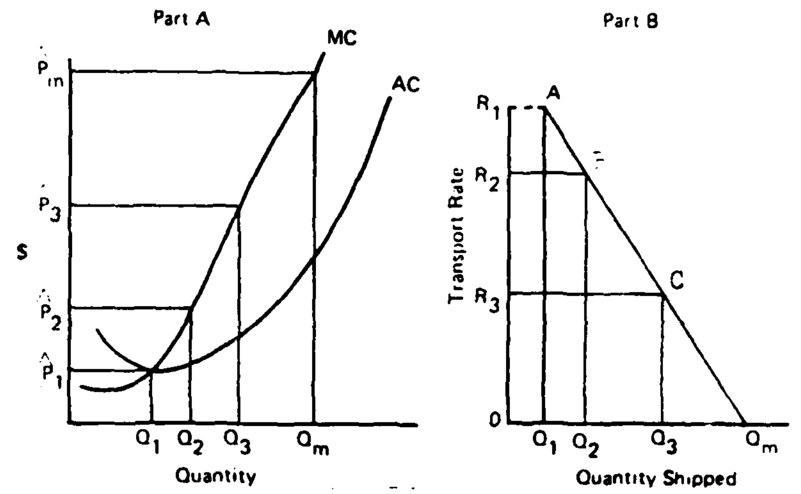


Figure 2

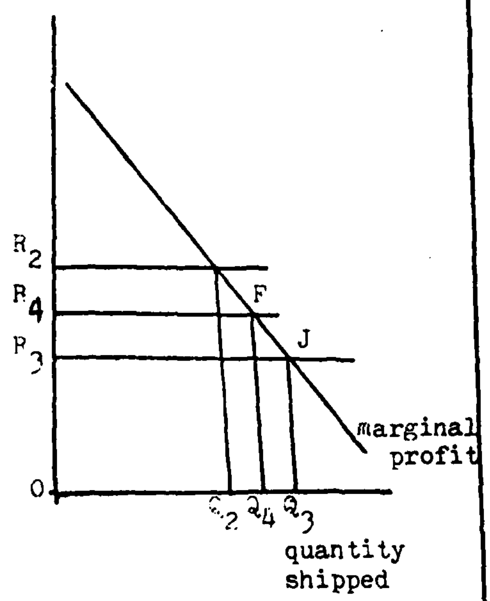
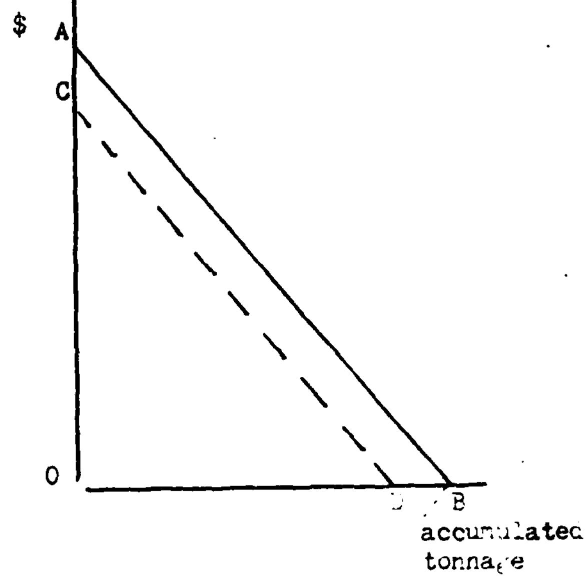


Figure 3



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